Final Master's Thesis

Master's degree in Energy Engineering

Short and mid-term energy storage technologies for the grid integration of wind parks

Thesis Report

Author: Marina Gil Sánchez
Advisor: Francisco Díaz-González
Call: July 2018

ETSEIB

Escola Tècnica Superior
d'Enginyeria Industrial de Barcelona

UPC

Abstract

Energy storage systems are key players in the green energy transition. They provide reserve for the variable renewable energy generators such as wind or solar. For national grids of any country all over the world, active power reserves are needed to maintain grid frequency stability, which means, to create a balance between power generation and demand.

In this document, the variable renewable energy generator studied is a wind park with generators type 4, not synchronised with the grid. A hybrid storage system composed by flywheels and lithium-ion batteries makes the project achievements possible: primary frequency control through a control droop using flywheels and power smoothing using lithium-ion batteries.

To complete the objective of this project, this document analyses the requirements of the grid codes and market regulations to provide ancillary services in Spain and develops an economical assessment over different study cases.

All data needed to complete this project are taken from free open-source databases on the internet (for wind park calculations, for frequencies of the grid and for day ahead market values). To complete the calculations, two different software have been used, MATLAB for wind park simulations and data treatment and GAMS for the optimization of the mathematical linear programing model.

Results from the fourth study case show that the hybrid energy storage system can be used to provide short and mid-term services for the wind park. It is economically feasible and the most important aspect is that the hybrid solution provides flexibility and scalability to the wind park operator in terms of integration to the grid.

Table of contents

List of Figures

List of tables

1 Glossary

EMS	Energy Management System
DoD	Depth of discharge
ESS	Energy Storage System
BESS	Battery Energy Storage System
FESS	Flywheel energy storage system
VRE	Variable Renewable Energy
WP	Wind Park
WT	Wind Turbine
REE	Red Eléctrica España

Key words

Primary frequency control, power smoothing, lithium-ion batteries, flywheel, wind park, hybrid energy storage system, mathematical optimization, economic feasibility.

2 Introduction

For this project, we are tackling the technology knowledge of an onshore wind park, its hybrid energy storage solution and its feasibility in the Spanish ancillary market service.

This study is important to continue reinforcing the alternative developments and improvements in the renewable electricity generation, encouraging to decrease of the enormous effects that fuel powered electric generators have in industrial activities and getting rid of the industrial-produced greenhouse gases such as carbon dioxide, methane and nitrous oxide. These are the main gases causing climate change.

Climate change is nowadays a very important governmental and social concern. The effects happening currently, known by the scientific community are:

- Frost-free season (and growing season) lengthen: a longer growing season would increase the growth of plants, that is good for oxygen production but will cause disturbances in the ecosystems. In addition, agriculture will be affected when facing a long frost-free season.
- Changes in precipitation patterns: heavy precipitation will continue increasing as well as less precipitation depending on the area. The point is that if it rains or snows in different sequences it may entirely alter how some species will live and evolve (fauna & flora).
- More droughts and heat waves: it will involve a reduction of moist soil, intense summer temperatures and less intense cold waves.
- Sea level rise: this is a result of a water volume magnification due to the melting land ice.
- Arctic ice-free: It will become ice-free in less than a century if it continues melting this quick from now on.
- Ocean acidification: the carbon dioxide absorbed by the ocean is increasing and it is having a crucial effect in the marine ecosystem.

In the atmosphere, CO_2 concentration is increasing and as many published papers/researches express, this is directly linked to the effects of human industrialized activities from the 19^{th} century until now, producing CO_2 concentrations up to 400 parts per million as Figure 1 shows.

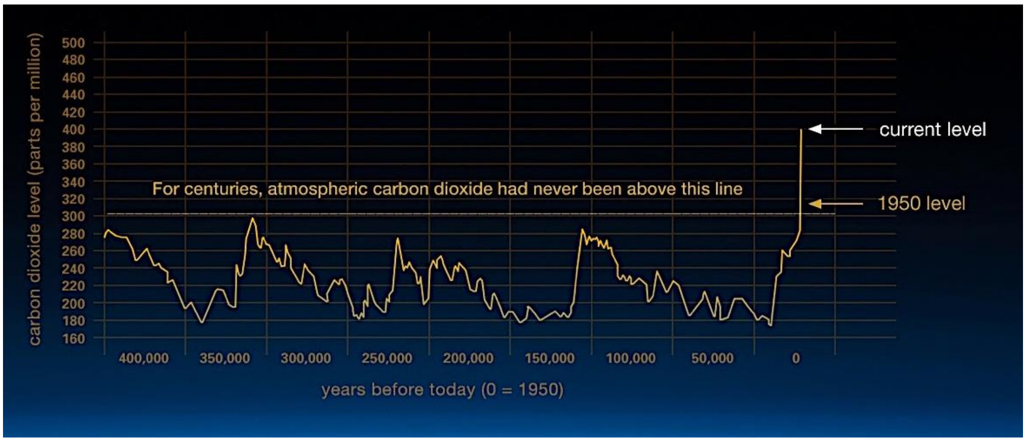


Figure 1 Clear evidence of human activity linked to climate change [1]

Global temperatures have increased by the same cause, gaining 1.1 degrees Celsius since the late 19th century [1].

As a consequence of the previous effects, renewable energies are having incentives and subsidies from governments. Policies are a key player in the reinforcement of renewable energy generation. Noticeably, not every country is following the green energy transition due to their politicians. However, from the EU they are boosting hard to reach a high share of renewables in the European grid [2].

- The European Parliament and EU member states were able to reach a compromise on a 32% renewables energy target by 2030. Deal on 14th June 2018
- The 2015 Paris Agreement on Climate Change remains in place: the binding target to cut emissions in the Union by at least 40% below 1990 levels by 2030

2.1 Objective of the project

The integration of wind parks' power in grids and their participation in ancillary services are the objectives to tackle. To do so, it is needed to face the flexibility problems due to the intermittent energy generation of wind parks. Consequently, grid-level energy storage systems can provide numerous benefits and support to the electricity system, such as renewable energy integration into the grid. It is as well considered a tool for grid decarbonisation.

The intermittences of a wind power integration mean serious impacts on power systems, such as system reserves, reliability and costs. Wind power intermittency can be mitigated by a series of technological solutions. In this project, the implementation of a hybrid energy storage system in a wind park is proposed.

The goal of the project is to develop a solution based on:

Wind park + Hybrid ESS to provide Primary Frequency Control and Power Smoothing

Specifically, the aim is to face the problem of optimizing the operation of energy storage systems and wind turbines at once.

The final study case will show that part of the total required power reserves for primary frequency control are provided by flywheels, rapidly reacting on grid frequency changes in combination to WT. In addition, batteries are included to the park so its output is constant regardless the variability of wind causing power smoothing.

To do so, it is needed a development of an Energy Management System (EMS). Two different software are used: MATLAB from MathWorks and GAMS from GAMS Development Corp.

For the purposes of the work, the wind park is to be intended as the aggregation of several turbines subjected at once to the same wind. The wake effects in the onshore WP are excluded from this study.

3 State-of-the-art

3.1 Wind power and energy storage technologies

Wind park

Wind parks are the combination of several wind turbines placed in the same location and connected between them to generate a large amount of electric power. Due to the feasibility and proven technology that represents a wind turbine, the number of wind parks are now thousands in many countries around Europe and they sum a total of 168,7 GW of capacity installed between onshore and offshore installations. See Figure 2.

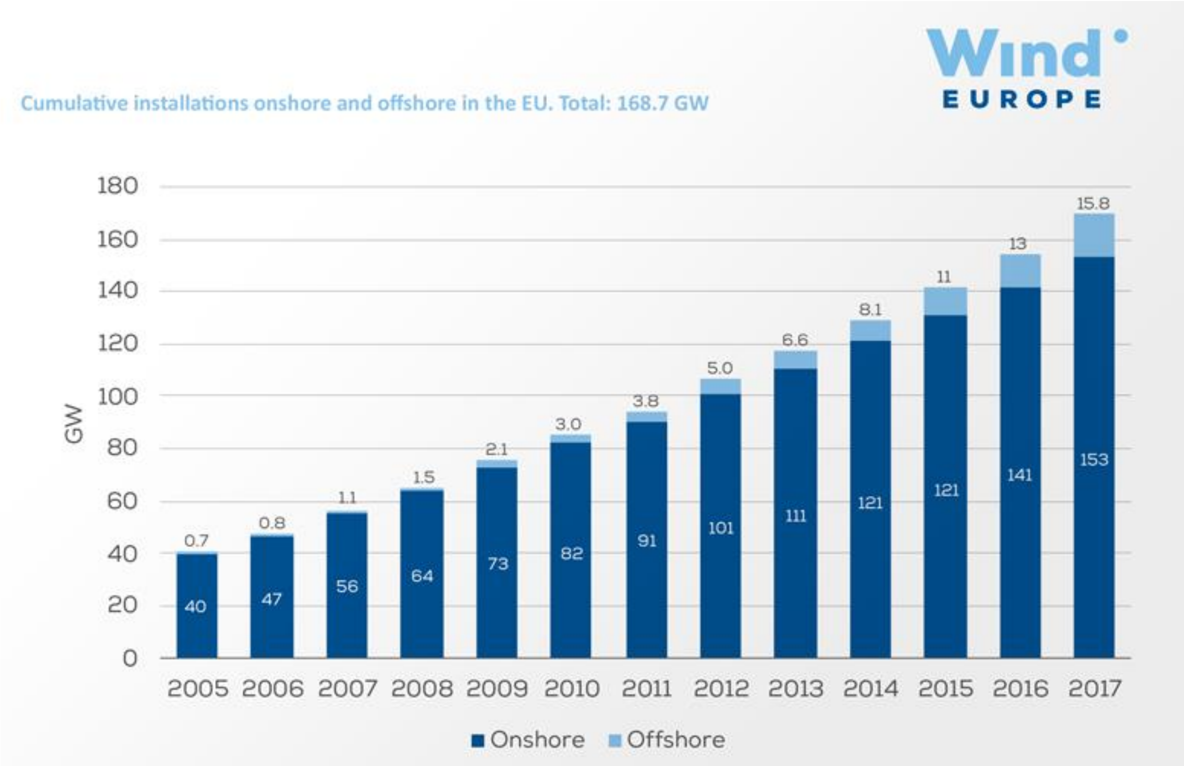


Figure 2 Cumulative capacity Onshore and Offshore Wind Power [3]

Wind energy now covers 11.6% of the EU's electricity demand; in other numbers, between 2011 and 2016, it has reduced by €32bn EU's fossil fuel import bill [3].

In Spain, wind energy covers the electricity consumption of 10 million households and it avoids the emission of 25 million tonnes of CO_2 per year [4].

The most common onshore WP connect different designs of horizontal-axis wind turbines for their power generation. The most used is a three bladed, horizontal axis, pitch-regulated WT operating at variable rotational speed. The gearless "direct drive" WT with a variable speed generator designs have a significant market share. Wind turbines generally start generating electricity at 3 to 5 m/s wind speed, reach maximum power at 13 to 15 m/s and cut-out at a wind speed of around 25 to 27 m/s [5].

The amount of power that can be taken from the wind depends on the length of the blade and the size of the turbine. The output is proportional to the dimensions of the rotor and to the cube of the wind speed. Next Figure 3 shows the main types of WT.

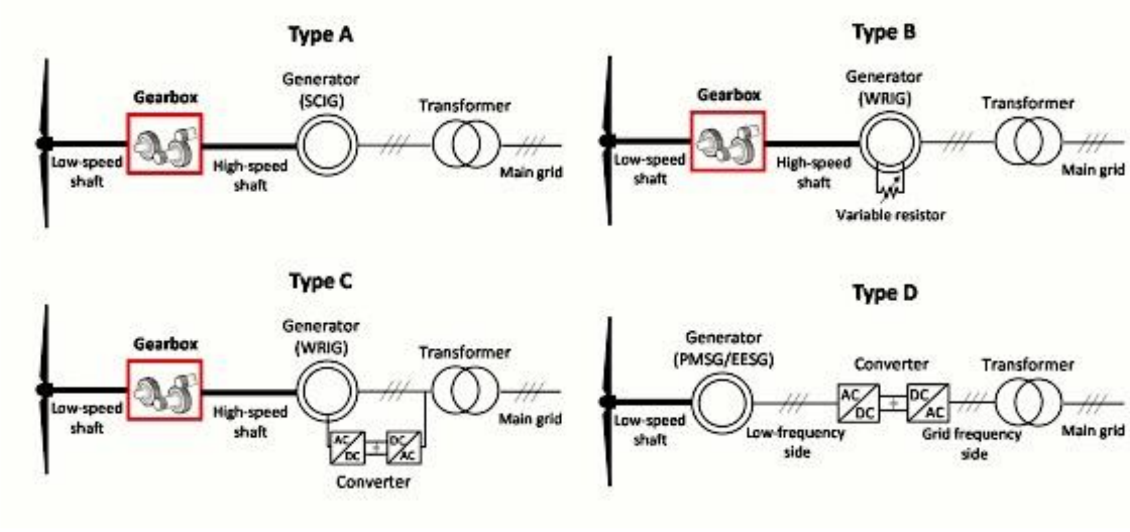


Figure 3 Types of WT generators [6]

- Type A: Fixed-speed generator. No power converter neither other speed regulation techniques are used in this configuration. It uses an asynchronous electric generator.
- Type B: The speed of the asynchronous generator is controlled by a variable resistance that enables modifying the circulating current in the rotor of the electrical generator. The electrical losses are high and the response to grid requirements is limited.
- Type C: Doubly-fed induction generator (DFIG). The power converter AC/DC controls the current from the electric generator’s rotor. Electrical losses are lower and the response to grid requirements is improved. The rated power of the converter is approximately 30% of the rated power of the WT because the converter is just connected to the rotor.
- Type D: The frequency on the generator side can be completely controlled and the gearbox is not needed. The synchronous generator is directly coupled to the shaft of the rotor. With the full power converter is easier to achieve enhanced grid services. The synchronous generator can be a wound rotor synchronous generator (WRSG), or a permanent magnet synchronous generator (PMSG).

In Europe, there is a prevalence of 2–3 MW turbines (with almost 50–50% of drive train arrangements Types C and D) but also an important number of high powerful wind turbines. Larger WTs use a Type D configuration [6].

Electric Energy Storage System

The electric energy can be stored in different energy forms: potential energy with water pumping systems, air compressed systems, electrochemical such as secondary batteries and fluid batteries, chemical energy with fuel cells, kinetic energy with flywheels, in magnetic fields with inductors, in an electric field through capacitors or in form of thermal energy with molten salts.

Firstly, here there are compared the most conventional and commercial electrochemical batteries in four different families: lead-acid, alkaline, molten salt and lithium-ion batteries. Each one has different characteristics that are shown in the next Table 1:

Table 1 Types of batteries and characteristics [7]

Type	Subtype	Op. Voltage (V)	Nominal Voltage (V)	Operative Temperature (C)	Cyclability[1]	Energy Sp.theoric and real (Wh/kg)	Monthly Self-discharge	Efficiency	Maximum discharged rate
Lead-acid battery	valve-regulated lead-acid battery	1,75-2,27	2,00	(-40;50)[5]	1200 (80% DoD;C/8)	170	2-4%	70-80%	1C cont.
	Flooded Lead-Acid Battery	1,75-2,23	2,00	(16;32)	1800 (80% DoD;C/8)	170	5%	70-80%	1C cont.
Alkaline	NiCd	0,90-1,5	1,3	(-20;60)	800 (80% DoD;C/8)	213	10%	60-80%	10C cont.
Alkaline	NiMH	0,90-1,5	1,3	(0;40)	800 (80% DoD;C/8)	240	100%	60-80%	1C cont / 5Cpeak (30s)
Molten Salt	NaS	2,31-1,63	2,1	(300;350)	4500 (80% DoD;1C)	783	0%	89%	1C cont / 5Cpeak
	$Na/NiCl_2$	3,10-1,72	2,58	(270;350)	3000 (80% DoD;1C)	790	0%	85%	1C cont.
Lithium-ion battery	$C/LiCCoO_2$	4,2-3,0	3,6	(-20;55)	3000 (80% DoD;1C)	709	<5%	>92%	1C cont. / 30C pulse
	$C/LiNiCoMnO_2$	4,10-3,0	3,7	(-20;55)	2500 (100% DoD;C/2)	837	<5%	>92%	5C cont. / 30C pulse
	$C/LiFePO_4$	3.6-2.5	3,3	(-30;55)	>3000 (100% DoD;1C)	479	<3%	>92%	35C cont. / 30C pulse
	$C/LiMn2O_4$	4.2-3.00	3,37	(-20;55)	>2000 (100% DoD;1C)	625	<5%	>92%	10C cont. / 40C pulse

[1] it is measured on how the electrochemical decomposition of the electrolyte will affect the cycle of the battery (the process of charge that returns to its beginning and then repeats itself in the same sequence when discharge). DoD (depth of discharge). C nominates the nominal capacity of the battery. The multiple of C determines the charge-discharge current [4].

From the table above, it is clearly chosen for this project any of the lithium-ion battery models due to several important characteristics: the most important one is the operational voltage of the cell that is about 4 times the other types, the efficiency, that is higher than 92% (the highest between the four types), the cyclability of lithium-ion batteries that is high and, the operative temperature that is inside our limits. The maximum discharged rate is another important characteristic of a battery, it can be defined as a multiple of the C rate or as the rate at which electrical current is removed from a cell or battery. The behaviour of using lithium-ion batteries within a wind park is the following:

When the power generated from the wind turbine is higher than what the demand/load needs then the energy storage system charges the batteries, and vice versa.

Batteries have enough energy storage capacity to exchange their rated power with the system they are connected to continuously and during several hours. In this sense, they can be used for different ends including primary frequency control or power smoothing of variable generating energy systems such as wind and photovoltaic parks.

Kinetic Energy Storage System

The second storage type used in this project is a flywheel energy storage system. Its implementation is very convenient due to its ability to store electrical energy from intermittence sources such as VRE. The FESS utilization in electricity grids is the following:

In the first step the FESS regulates power coming onto the grid from intermittent VRE, in this case from a wind park. In the second step, the flywheel uses a rotor that is a high-speed spinning mass to store kinetic energy in the heavy solid steel flywheels until it is needed. In the last step, when the energy is needed, the flywheel converts it back into electricity and propels it back onto the grid as shown in Figure 4.

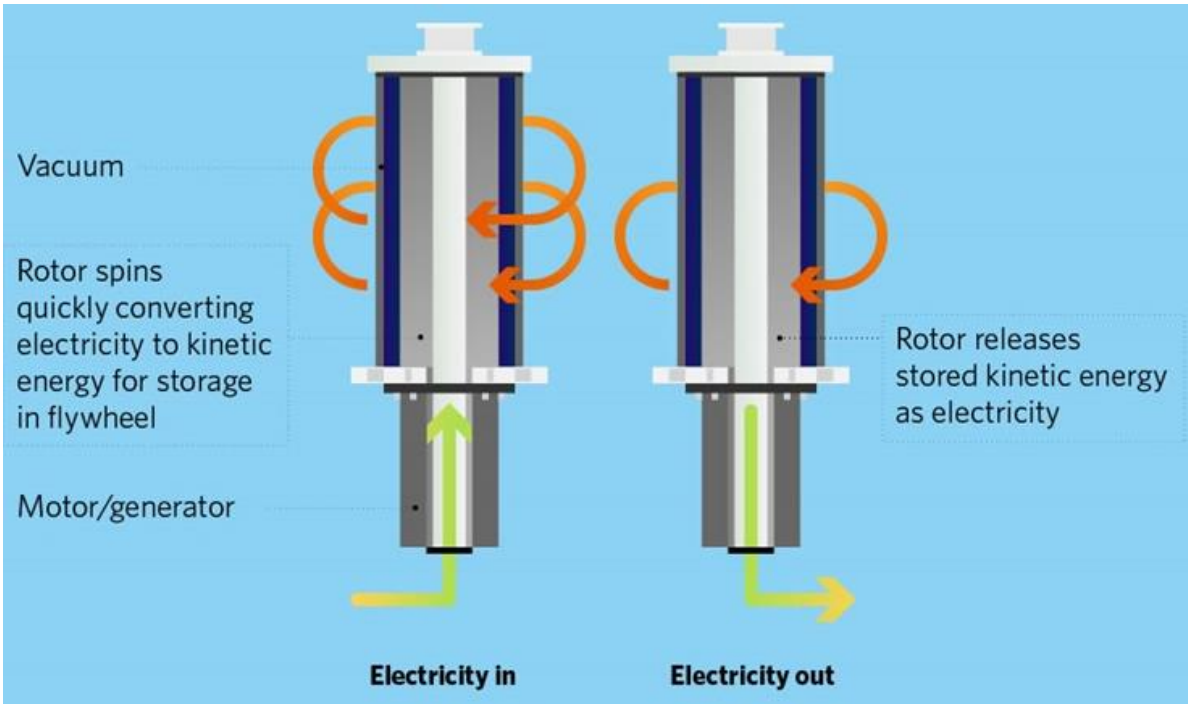
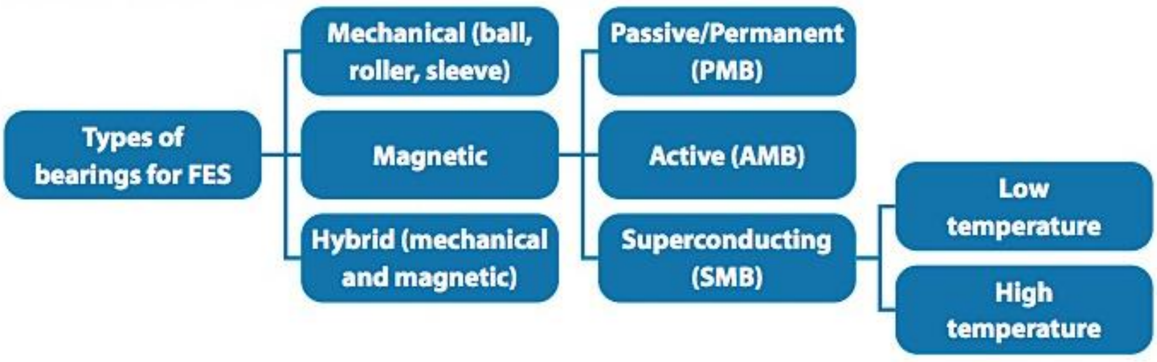


Figure 4 Flywheel scheme [8]

The system is characterized by high energy density compared to lithium-ion batteries or any other energy storage system (up to 10 kW/L). It gives a fast response when a peak of energy is needed, it means a fast response to voltage changes. It can achieve hundreds of kW peak. The energy storage increases with the rotational speed and the mechanical voltage in the wheel, therefore it exists a restriction in the materials. The energy stored by the flywheel is dependent on the square of the rotating speed and its inertia. The moment of inertia of the rotating mass is a function of its mass and shape. Two types of flywheels have been developed: low-speed (up to 10000 rpm) and a high-speed (up to 100 000 rpm) [9], [10].

Another characteristic is that the atmosphere inside the flywheel is very low to reduce mechanical friction and air friction. It has a wide operating temperature rate, and high energy density. The efficiency is usually high (around 90% at rated power) but it depends on the manufacturer [9].

The lifetime of a flywheel, up to 1 million cycles, does not depend on the load level or the number of discharges [10]. There are already in the market flywheels that use permanent magnetic bearing (PMB). A friction-free bearing eliminates the problems of the mechanicals ones [7], [11]. In addition, another technology that is recently used are the active magnetic bearings (AMB) that support the rotating rotor’s shaft with the magnetic field created and have no mechanical friction [12]. Other types are shown in Figure 5.



Source: International Renewable Energy Agency, based on Daoud *et al.*, 2012.
Note: FES = flywheel energy storage; PMB = permanent magnetic bearings; AMB = active magnetic bearings; SMB = superconducting magnetic bearings.

Figure 5 Types of bearings for flywheel energy storage systems [13].

Flywheel Energy Storage Capabilities [14]:

- Voltage and power quality support: The flywheel could provide active and reactive power to balance local power fluctuations caused by, in this case, renewable energy sources. It helps to improve power quality and stabilize voltage levels at the local distribution level.
- Ramp rate control: The rapid response of the flywheel helps to control the big and not wanted ramps (higher than 10%), eliminating them results in smoother power output.
- Frequency control: The rapid response of the flywheel allows a direct frequency control providing a short-duration grid balance while the main system (in our case the wind park) recovers.

Main characteristics [14]:

- Fast charge capabilities
- High power density, independent of stored energy level
- Millisecond response: 3 to 5 times quicker than typical generators
- Balancing of the grid
- Low lifecycle cost with minimal maintenance over 20 year operating life
- Fully recyclable and uses non-exotic materials
- No harmful chemicals or emissions are released while operating
- Full depth of discharge capability with unlimited cycling, without loss in performance

Wind park and energy storage system proposal

For this project, it is proposed an onshore wind park located in Spain. With the explanations given in this section, it is finally proposed a wind park in combination with an energy storage system based on lithium-ion batteries and flywheels to complement and improve the flexibility and feasibility of the WP. See the Figure 6 to have a simple and general perception of the concept.

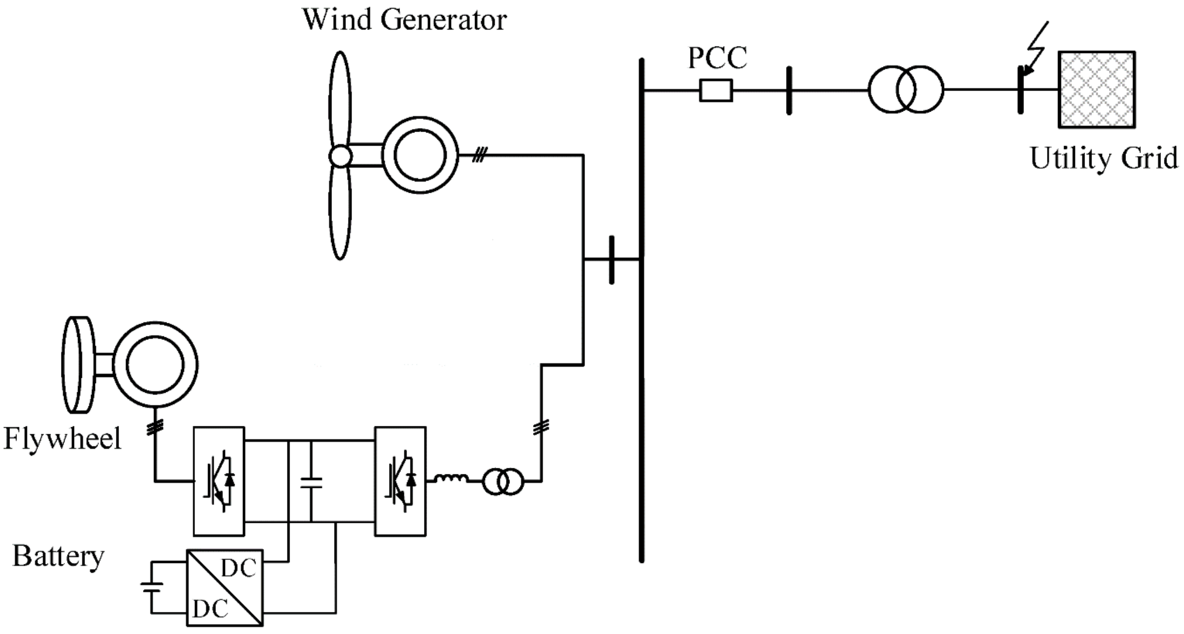


Figure 6 Simple scheme of the study case (own elaboration)

The Flywheel energy storage system is connected to the wind generator terminal through a coupling transformer, a voltage source converter (from the wind generator side), a voltage source inverter (from the flywheel side).

The electrochemical battery storage system composed by a DC-DC (buck-boost) converter and it connects to the same voltage source converter from the wind generator side.

As said before, to achieve the goal of this project from this scheme the flywheels will provide the power reserves for primary frequency response together with the WTs and the batteries will provide power smoothing.

3.2 Literature review on applications of energy storage technologies in wind parks

As mentioned in Fabio Monforti et al. [15], the high penetration of renewable energy sources in the existing grid depends on how precise are studied the spatial and temporal features of the intermittent power generation to be able to supply electricity to the system. For wind energy, there are two main parameters that need to be known: uncertainties in the wind power assessment from the wind technology knowledge and uncertainties originated by meteorological issues. Wind power intermittency is the major barrier and main flaw of large scale wind power farms.

Due to the intermittences that are created by wind energy generation, the electricity markets work mostly on hourly schedules. Differences between productivity forecasted and real production require a balancing from a backup system [15].

Technological solutions can mitigate wind power intermittency like for example energy storage systems. The excess wind power generation is stored in ESS during off-peak demand periods. During peak demand periods, the energy stored is released to supply electricity. The positive effects of including a ESS is the output smoothing, time shifting, frequency regulation, alleviate transmission congestion, reserve application emergency power supply, etc. amongst others [16]. Check Figure 7 for power balancing output with an ESS.

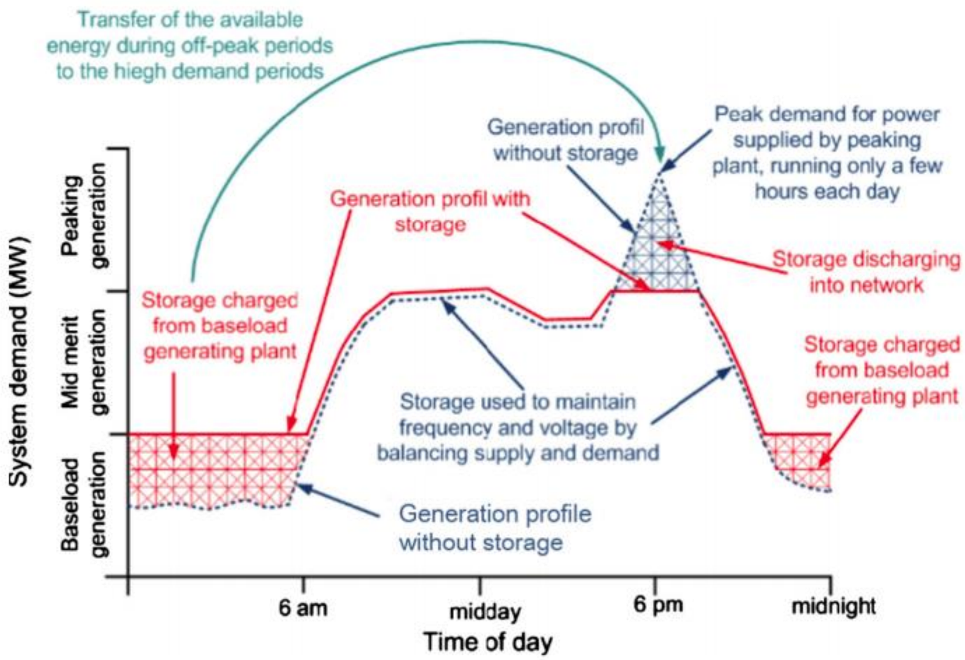


Figure 7 Power balancing with an ESS [17]

As it is mentioned in Díaz-González et al. [18], in case a wind park is willing to participate in primary frequency control, the wind turbines must not be operated at maximum available power, they should operate with a 10 % margin (then, a 90 % capacity). The WP operator loses while deloading 10 % of its revenues. In this case, again, technological storage solutions are key to be able to extract the maximum available power from the wind.

That 10% margin during network disturbances can be reduced (depending on wind speed) using flywheels as the ESS. The results are that using a flywheel with a characteristic of “Ratings of flywheel-based storage plant 20–30 MW-min” and a “Rated power of wind power 500.0 MVA” the advantage is remarkable; for wind speeds of 7 m/s the flywheel share of power reserve allocation is a 120 %, for wind speeds of 8 m/s the flywheel share of power reserve allocation is a 79.3 % and for wind speeds of 9 m/s the flywheel share of power reserve allocation is a 55.7 %, letting the wind turbines operate at full capacity and maximum efficiency reducing the need to operate in deloaded mode [18].

Another type of ESS for frequency response in a WP is a Vanadium Redox Flow battery (VRB). As mentioned in Johnson et al. [19], the ESS will store energy absorbed from high-frequency response events and release it during low-frequency events. This process would let the WP to operate closer to the maximum level extracting the maximum available power from the wind as mentioned before. The interesting point from that article to this project is the economic optimization study that was developed to calculate the size of the ESS. The methodology taken followed the next formulation steps: Definition of the objective function components, definition of the objective function, global balance constrains, wind turbine restrictions and storage restrictions equations.

As mentioned in Motin Howladrer et al. [20], there are several power smoothing methods for wind energy conversion systems. There are mostly two different types: With energy storage equipment such as batteries, flywheels, fuel cells… and without energy storage equipment such as inertia, pitch angle control or others... For the case of electrochemical batteries in a wind park, the behaviour is that when the power generated from the wind turbine is higher than the smooth line power reference signal then the energy storage system, electrochemical batteries, charges and vice versa. This way it is ensured a smooth power delivered to the power grid. For the case of a flywheel based power smoothing, the FESS stores energy when more power than needed is generated from the wind turbine and it discharges when the wind turbine is delivering less power. As before, the final in-feed to the grid is a smooth output power.

From Wang et al. [21] paper, it is possible to find experimental results of the power smoothing methods with a FESS integrated in a wind farm. As a result of this paper it can be checked in Figure 8 that it is possible to have a smooth control strategy for a flywheel and contribute to the stable operation of the power grid.

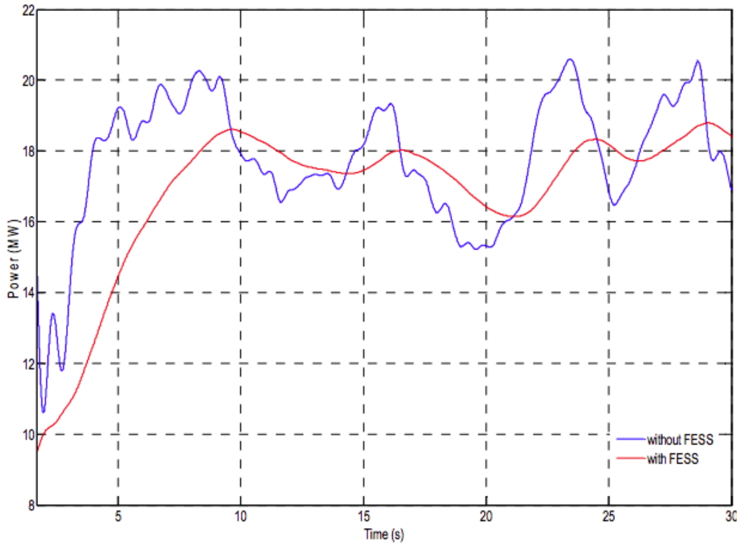


Figure 8 Curve of active power output of a wind farm with and without FESS [21]

From Khalid et al. [22] an aggregated battery storage system in a wind park works as it can be shown on Figure 9 from this paper. The output signal is smoother based on simulation results.

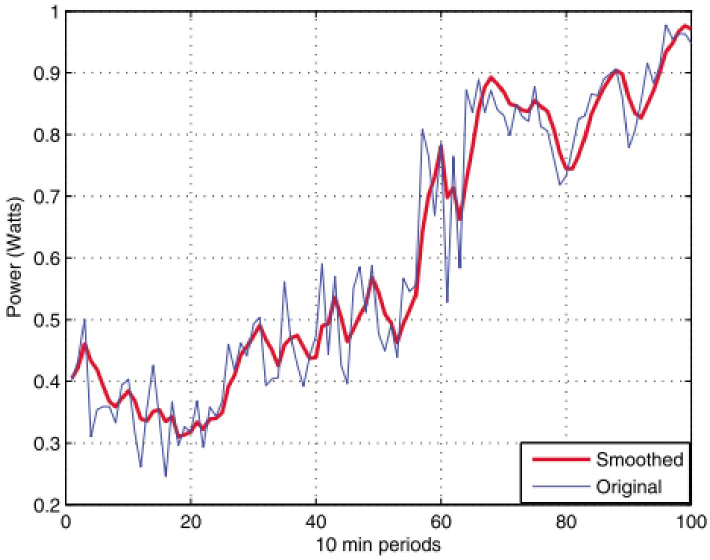


Figure 9 Wind power smoothing with aggregated battery energy storage system [22]

Between these two experiments Figures 8 and 9, it can be checked how the active curve from the flywheel is contributing to the grid from 0 to 30 seconds and conversely, battery energy storage helps support the grid after minutes.

3.3 Current wind data and existing hybrid projects

Global wind energy installations capacity installed was 433 GW as of the end of 2015. Annual reductions in CO_2 from existing wind parks were about 521 million tonnes in 2015. By 2030 it is estimated that wind power could reach 2110 GW, supplying up to 20 % of world electricity, reducing CO_2 emissions by 3.3 billion tonnes per year. Wind has become a mainstream power source. By 2015, wind energy provided around 4 % of global electricity supply [23].

Specifically, in Spain, there is a total of 96 MW that supposes a 0.6 % of the total installed capacity in EU. In the EU, the country with the highest capacity installed in percentage is Germany, followed by the UK and France with 42.0 %, 27.2 % and 10.8 % respectively (check Figure 10 below). Even if these countries have more share in wind power in Europe, it does not mean that they are covering the demand they need, in the Figure 11, the three countries that by 2017 covered a higher percentage of the electricity demand were Denmark, Portugal and Ireland with a 44.4 %, 24.2 % and 24.0 % respectively. Spain is in the fifth position of the ranking [3].

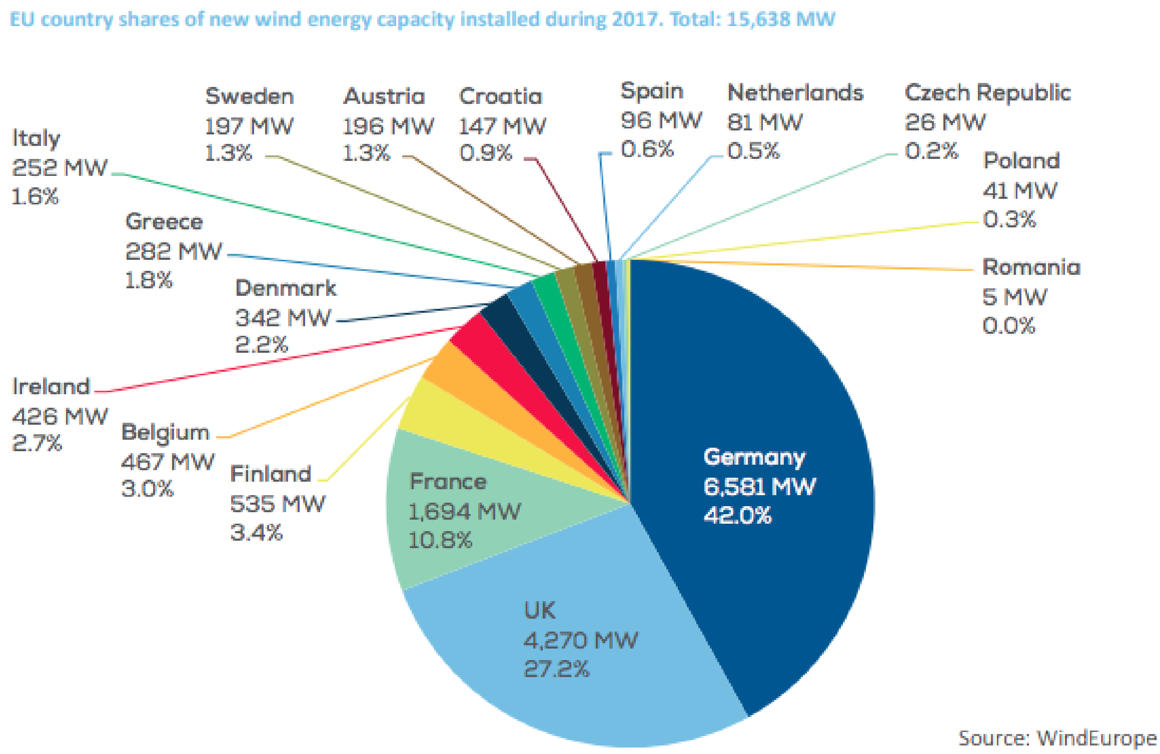


Figure 10 Shares of Wind Power in EU [3]

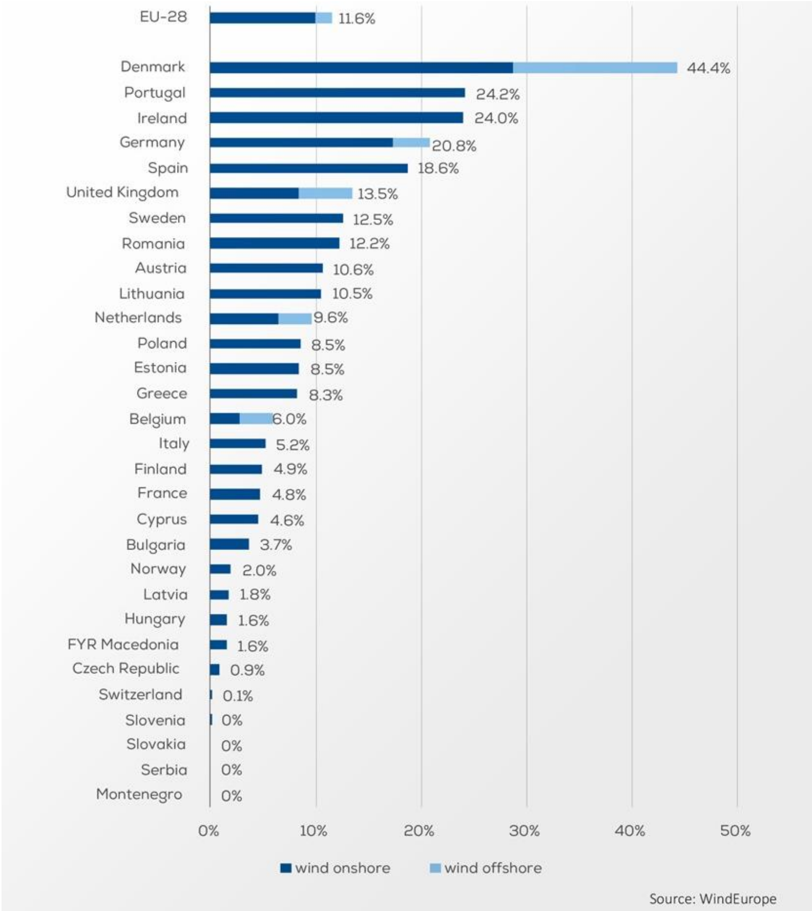


Figure 11 Percentage of the average annual electricity demand covered by wind [3]

In Spain, 77 % of the primary energy consumed comes from fossil fuels and it is imported. Renewables would avoid the 1.9 billion euros per year spent for their importation [4].

According to the market research firm IHS, the global energy storage market is growing to an annual installation size of 6 gigawatts (GW) in 2017 and over 40 GW by 2022. Flywheel and electrochemical battery energy storage systems are currently operating in the competitive ancillary services power market [17].

The only wind power storage plant in Spain has a combination of one aero generator, grid-connected, and electrochemical batteries. It was designed by ACCIONA and it is located in Navarra [24]. The system is formed by a 3-megawatt rated capacity AW116/3000 wind turbine and two batteries of Li-ion Samsung SDI technology: one fast-response 1 MW / 0.39 MWh that can maintain 1 MW of power for 20 minutes, and another one of slower-response with longer autonomy of 0.7 MW / 0.7 MWh, it can maintain 0.7 MW per hour [24]. This means that the storage technology is not proven enough in Spain and there are still many opportunities for studies and implementations.

Internationally, the largest hybrid wind power stored plant is located in South Australia. The lithium ion power pack battery has a capacity of 100 MW and can supply 129 MWh of energy to the grid (power delivery for around 30,000 homes), a total of about 1 hour and 18 minutes of power delivering at full capacity. It is installed at the Hornsdale Wind park that has a capacity of 315 MW [25].

Temporal power, a Canadian flywheel manufacturing company, is working with the utility Hydro One to provide up to ten 500 kW flywheels, for frequency regulation on a feeder that is connected to two 10 MW wind parks in Ontario. The flywheel is able to provide between six to fifteen minutes of storage energy with a millisecond response to balance wind ramping. The system started working in 2014 and it is currently in operation. The integrated flywheel system gives to the Utility Operator a gain of 2 MW of regulation service in the grid [5].

A hybrid combination of a power pack battery storage system and a flywheel storage system has been installed in Europe, Ireland. The pilot system includes two flywheels of 160 kW / 30 kWh by US manufacturer Beacon Power and a Hitachi Chemical 160 kW / 576 kWh deep-cycle lead-acid battery. The grid support response service is estimated to be in less than 20 milliseconds [26], [27].

A hybrid combination of a power pack battery storage system, a flywheel storage system and a wind park has not been tested yet and currently, there are no existing projects. That is why this project has been developed.

4 Methodology

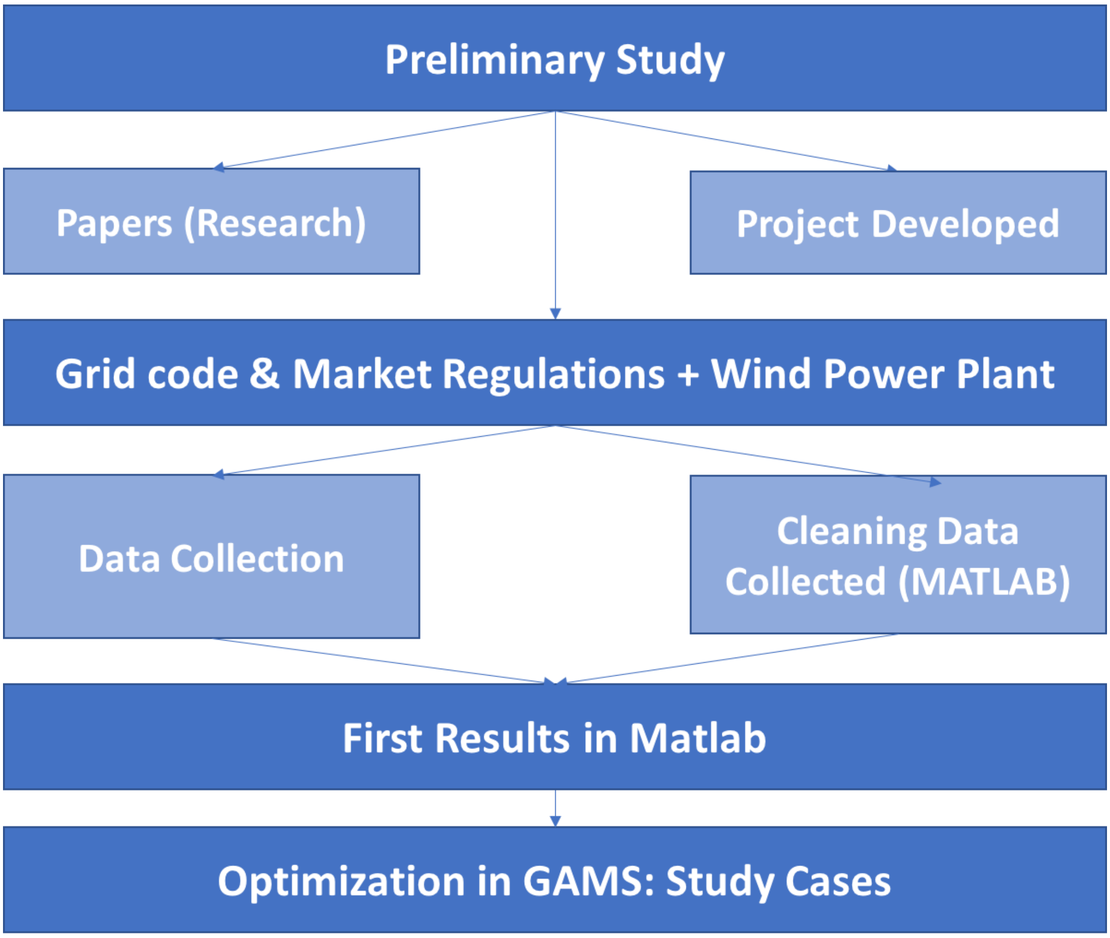


Figure 12 Methodology followed (own elaboration)

Figure 12 shows the methodology followed to solve this project. To start this project the first steps have been the study and analysis of current papers and technologies still on a research phase and others projects developed in a more settled and operational stage. To continue, regulations and where to locate the wind park were important steps. Only updated regulations are the ones used for this project since it is important to reach a realistic solution. In the case of the wind park, national laws have been checked for setting it and the respective prohibitions. After this step, all data collected needed to be treated in MATLAB through different MATLAB codes that can be found at the end of this document in the Annexes. From that processed data some results have been gotten. However, main solutions are achieved at the end of the project when the final mathematical optimization in GAMS is done validating the study case presented in this project.

5 Review of regulations: grid codes

As it was said in section 1, the main challenge of this project is to provide frequency regulations and power smoothing. In this chapter, the regulations of the European grid code are going to be studied.

5.1 General grid code requirements in Europe

The grid codes are fundamental for a successful penetration of variable renewable energy generation (i.e. wind energy) within the grid. Grid codes are different between countries, because they depend on needs and conditions of local power systems, and they provide the rules for the power system and energy market operation, contributing to system stability, reliability and security of supply. In Europe, the rising share of wind parks will make grid operators have stricter requirements.

As known from section 3, the active power output of VRE generators depends on the weather. Renewable generators such as wind turbines have different technical properties from fossil-fuel power stations. Thus, technological innovation parallel with the development of grid codes has allowed VRE generators to help stabilise the network. For example, VRE generators can now provide reactive power for voltage control, active power reduction during congestion or over-frequency events, and network support during faults.

The grid code connection for VRE generators provides technical support and requirements for the wind park when connecting to the electricity grid. Moreover, grid codes let network operators, generators, suppliers and consumers act effectively in the electricity market. There are four types of grid codes (shown Figure 13) and in this project the study is based on Operating Codes (within the point of Load Frequency control and reserve code).

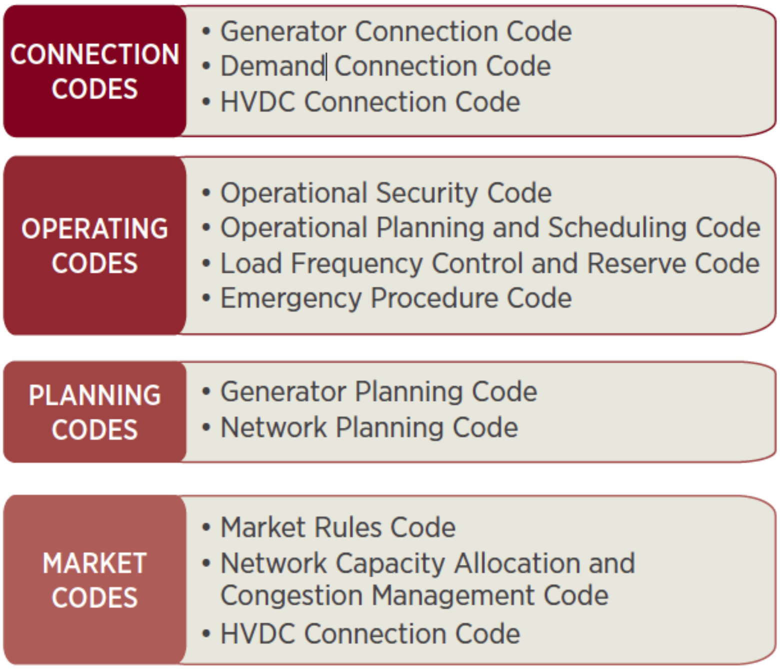


Figure 13 Different types of grid codes from IRENA [28]

In Europe exists ENTSO-E, the European Network of Transmission System Operators, and it represents 43 electricity transmission system operators (TSOs) from 36 countries across Europe (Spain is one of them). ENTSO-E members share the objective of setting up the internal energy market ensuring its optimal functioning. One of the important points is the integration of a high degree of Renewables in Europe's energy system and the development of constant flexibility [29].

Grid codes within Europe are a set from regulations drafted by ENTSO-E, with guidance from the Agency for the Cooperation of Energy Regulators (ACER), to facilitate the harmonization, integration and efficiency of the European electricity market.

5.2 Grid code application

In Spain, Red Eléctrica de España (REE) is the grid electricity system operator and distributor. Clarifying what is happening in Spain, there is no specific grid code and the network is regulated with the general restrictions of Europe.

The applicable regulation is the one "**establishing a network code on requirements for grid connection of generators from the Commission Regulation (EU) 2016/631 of 14 April 2016**." Please check the Annex A to see the articles from Commission Regulation (EU) 2016/631 of 14 April 2016 that are applicable to this project [30], [31].

Definition of the regulation: << *This Regulation establishes a network code which lays down the requirements for grid connection of power-generating facilities, namely synchronous* *power-generating modules, power park modules and offshore power park modules, to the interconnected system. It, therefore, helps to ensure fair conditions of competition in the internal electricity market, to ensure system security and the integration of renewable electricity sources, and to facilitate Union-wide trade in electricity* [30], [31]. >>

In this project, we are focusing on **primary frequency control** (and power smoothing). It is designed to create a route for market for providers whose services may otherwise be inaccessible (mostly for renewable power plants). This service gives to the service providers and to the grid (REE) an agreed stability upon price incertitude under the mandatory service program.

The primary frequency control from a generator group represents the ability of its system to modify its current active power in-feed to the grid in a short period of time. It can be either generation increase or decrease depending on the grid frequency fluctuation, this way, the frequency perturbations in the grid due to unbalances in the power supplied can be balanced.

Frequency tolerance in the Spanish network is around ±1.6 % of the nominal value, 50 Hz. The operational limits are shown in the next Table 2. A too high-frequency indicates a surplus of generation (more power than needed injected into the grid) and a too low-frequency indicates that the demand is higher than the generation. Both cases need to be avoided.

Table 2 European continuous operating frequency range [32], [33]

Frequency of power system (Hz)	f_{min}(Hz)	f_{max} (Hz)
50	47.0 to 49.5	50.5 to 52.0
60	57.0 to 59.5	60.5 to 61.8
Spanish frequency system, 50 Hz	49.2	50.8

System frequency is constantly changing and should be controlled by REE determining a good balance between generation and demand. Normal frequency variations in Spain go from 49.85 to 50.15 Hz [34].

Table 3 shows the parameters followed by Spain for primary frequency control for the generating units categorized “***Type C”*** in the European regulation that cover wind parks.

Table 3 Parameters for primary frequency control [30], [31].

Parameters		Ranges
Active power range related to maximum capacity $\frac{\lvert\Delta P_1\rvert}{P_{max}}$		1,5-10 %
Frequency response insensitivity	$\lvert\Delta f_i\rvert$	10-30 mHz
	$\frac{\lvert\Delta f_i\rvert}{f_n}$	0,02-0,06 %
Frequency response deadband		0-500 mHz
Droop s_1		2-12 %

In a wind park, there are several techniques to control the frequency, but all of them depend on the type of generator. There are three main types of generators currently in use in Spain: a full converter WT, a Double Fed Induction Generator (DFIG) WT or a Squirrel Cage Induction Generator (SCIG) WT as can be shown in Table 4.

Table 4 Grid Code implementation for different WT generators [29]

Requirement	Full converter WT	DFIG WT	SCIG WT
Frequency support	Full control, maximum if subject to wind conditions	Full control, maximum if subject to wind conditions	Limited controllability via pitch and/or rotor resistor

In the case of synchronous generators, the generators are synchronous with the REE, namely, the frequency of rotation is multiplied by the number of poles is exactly the frequency of the electric system (REE). If there is a change in the active power load (demand) then the frequency will change. This is what is called WT inertia. This WT always work at deloaded mode (90% capacity).

In full converters WT generators, the rotor is not synchronized with the grid but it is connected through power electronics. The power electronics, enable the 100% of generator decoupling from the grid frequency. This way, the frequency is easily controlled as well as the power operating point (controlling the rotational speed). In the case of a DFIG, the converter covers around 30% of the energy generated by the WT. Lastly, for the SCIG the control is mechanic and difficult to achieve.

The different operational modes from different types of WT can be easily checked in the Figure 14, from the Díaz-González et al. paper [33].

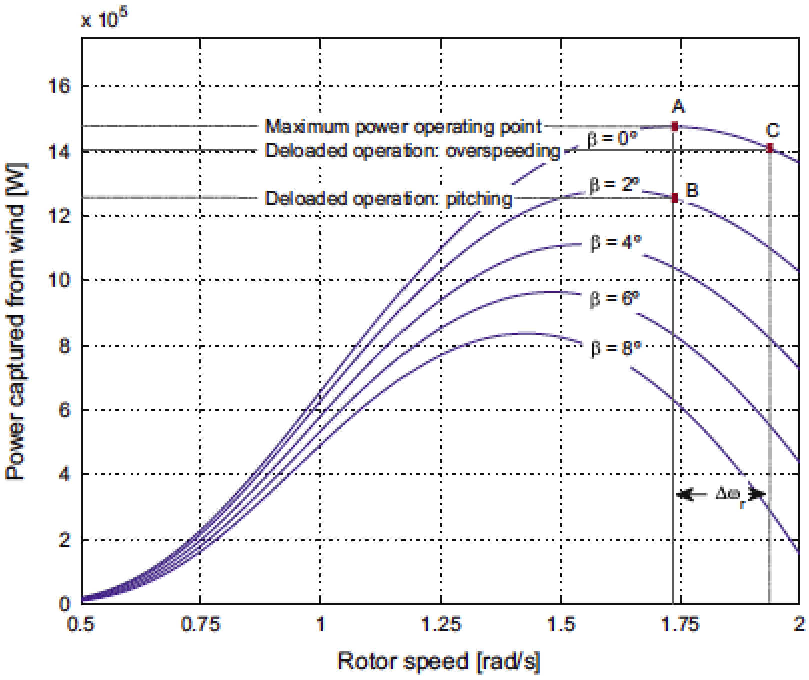


Figure 14 Power rotor-speed curves - deloading by pitching or over-speeding [33]

In this project, a full converter WT with a hybrid storage solution is used. The power operating point is maximum because there is no need of deloaded operation by over-speeding or pitching since the storage system can provide that extra active power needed to feed-in the grid. It will be shown in next Section 9.

Figure 15 has been created to understand better how the frequency affects to power generation in case of using a Full converter WT. Though also, to stablish droop control configuration for this project.

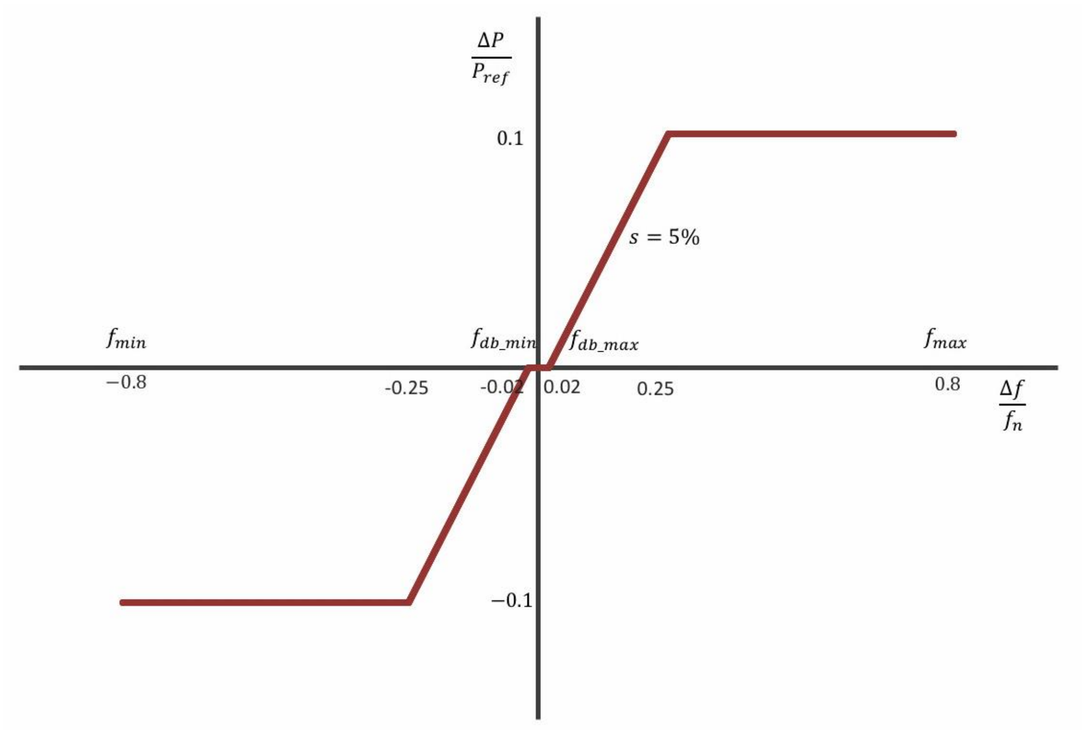


Figure 15 Spanish frequency grid code (own elaboration)

The Figure 15 above shows different frequency levels:

- f_{min} and f_{max} are the minimum and maximum instantaneous awaited frequencies. For the case of Spain, the values are the ones shown in Table 2, 49.2 and 50.8 respectively.
- f_{db_min} and f_{db_max} are the limits of the frequency dead-band. Within this interval, primary frequency control is not needed to be activated. For our case, 200 mHz (inside the limits of Table 3)

The term f_n, is the nominal frequency (50Hz), Δf is the frequency deviation in the system. The required range for the nominal power of the wind park is between 1.5% and 10%, and a 10% has been chosen. P_{ref} is the reference active power to which ΔP is related and ΔP is the active power output change from the power generators.

Having a negative values on the frequency axe means that more generation is needed. On the other hand, having positive values means that the wind park is generating more than needed and finally, having a 0 value (dead-band) means that no action is needed.

The droop characteristic presents a slope from 2% to 12%. It is represented by s and it is the slope of the curve and represents how the power generator behaves when changes in frequency. It is finally settled in a 5% (inside the limits of Table 3). Next equation (5.2.1) shows the droop required.

$$s[\%] = 100 \frac{|\Delta f|}{f_n} \frac{P_{ref}}{|\Delta P|} \quad (5.2.1)$$

Control droop or the relation power/frequency, refers to a change in the power output of the turbine proportional to the change in the frequency. The slope of the frequency droop has a high influence on the stabilization level of frequency. The droop control is implemented in the MATLAB code (Annex B) to get the final power due to frequency variations by a step time.

The droop controllers activate automatically the primary frequency control from the speed regulators of the full converter generators. The mission is to stabilize the frequency perturbations in the grid due to unbalances in the power supplied.

Having into consideration the general European grid code and the full converter type of generator of the wind park, there is no need to work in deloaded mode if using a ESS solution that supports the possible fluctuations and provide the power reserves.

The hybrid ESS solution will help the system when episodes of under-frequency or over-frequency occur, it will provide the extra energy need or will charge when there is no need to supply more energy to the grid respectively, following the slope of the droop control.

As a first impression, it seems that having a storage system will provide a higher revenue to the wind park owner due to the possibility of operating at maximum possible power any time of the day.

5.2.1 Other specifications for primary frequency control in Spain

When there is an unbalance decrease/increase in the Spanish grid frequency, there is an automatic increase/decrease in the active power from a generator group. The Spanish BOE-A-1998-20053 regulation says the next [35]:

- Primary frequency control: The system operator (REE) will determine the 31st of October of every year the requirements of the electric system for the following year.
- The generators group must have a capacity variation the capacity up to 1.5 % of the nominal power if needed for the grid.
- For frequency variations lower than 100 mHz, the primary frequency control needs to be accomplished over a period of 15 s while for a frequency variations up to 200 mHz, the primary frequency control needs to be accomplished between 15 s from the time the frequency changed and up to 30 s to complete the stability.
- Primary frequency control needs to be maintained at that level from those 30 s to 15 min (until the power deviation is completely offset by the next service, secondary or tertiary reserves) [36] [37].

The minimum offer value a renewable energy generator needs for the participation in the primary frequency control service is 10 MW. That value could be reached by combining several renewable energy generators if one is not able to achieve 10 MW.

5.2.2 Frequency data collection

In Spain, there is no a free open-source database where it is possible to check the frequency data of a complete year. For this case, it was needed to check if other Europeans countries had an open-source with this kind of information. Finally, the frequency data from 2016 was obtained through the National Grid of the UK. This frequency data is compiled by months and for every second [38].

It is important to clarify that in the UK the Primary frequency control is called FFR (firm frequency control) and it involves not only primary services but also others.

5.2.3 Cleaning data collection

Because this project is optimized with GAMS software, the frequency data was treated through a MATLAB code, as GAMS is limited by the quantity of inputs it can process. It was not possible to have a second-by-second optimization program and it was decided that we were going to take frequency data every 15 s for every day of the year. Check the MATLAB code in Annex B. The behaviour of the data collected and treated from the National Grid UK is shown in Figure 16.

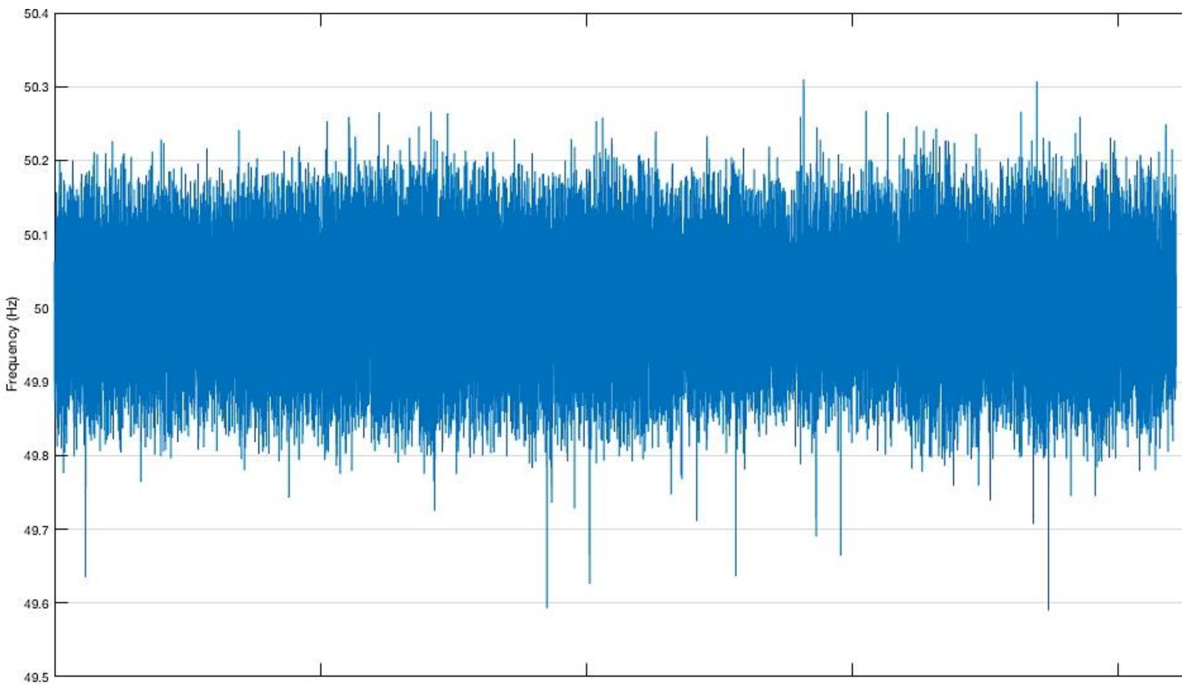


Figure 16 Frequency variation for the 12 months every 15 s (own elaboration)

From the National Grid UK, it is shown that frequency is inside the range 49.2 – 50.8 Hz. As a conclusion, in 2016, in the National Grid UK there was no episode (blackout) that could damage the grid and the equipment supporting it.

The maximum frequency value for the entire year is 50.31 Hz and the minimum value is 49.59 Hz. These values are far from producing a fault in the system grid, they are inside the interval that National Grid UK accepts (and the REE from Spain as mentioned in Table 2).

Nonetheless, this frequency variation is high in comparison with what happens in the Pan-European electricity grid because the UK is an island and they do not have a strong system as Continental Europe has. The UK grid is connected to European and Irish electrical grids (another Island) by submarine power. The connections with continental Europe are through HVDC cables to northern France, the Netherlands and Norway as can be checked in the interconnected network of Continental Europe, 2017 created by ENTSO-E [39].

In Spain, REE does not offer grid frequency data, so its behavior is unknown, other European countries, i.e. the Netherlands, has been taken to check how the grid normally variates in Continental Europe.

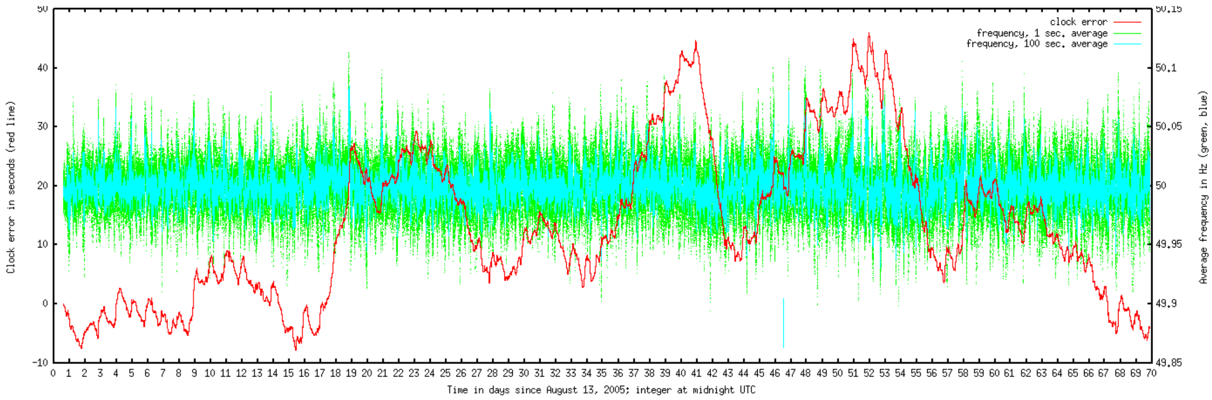


Figure 17 Frequency variation in Netherland [40]

As it can be checked in Figure 17, the frequency has so far rarely deviated more than 0.2 % from the nominal frequency, 50 Hz. Variations between 49.9 and 50.1 Hz are observed.

On the whole, it was not possible to get frequency data from any country within continental Europe so, our simulations are governed by UK data with higher variations that what will happen in Spain or any other country inside the Pan-European electricity grid.

5.3 Storage compatibility with grid code requirements

Primary frequency control service is completely compatible with the two storage systems that are being used: Li-ion batteries and flywheels. Figure 18 from IRENA shows perfectly how the storage system could be used depending on the different applications.

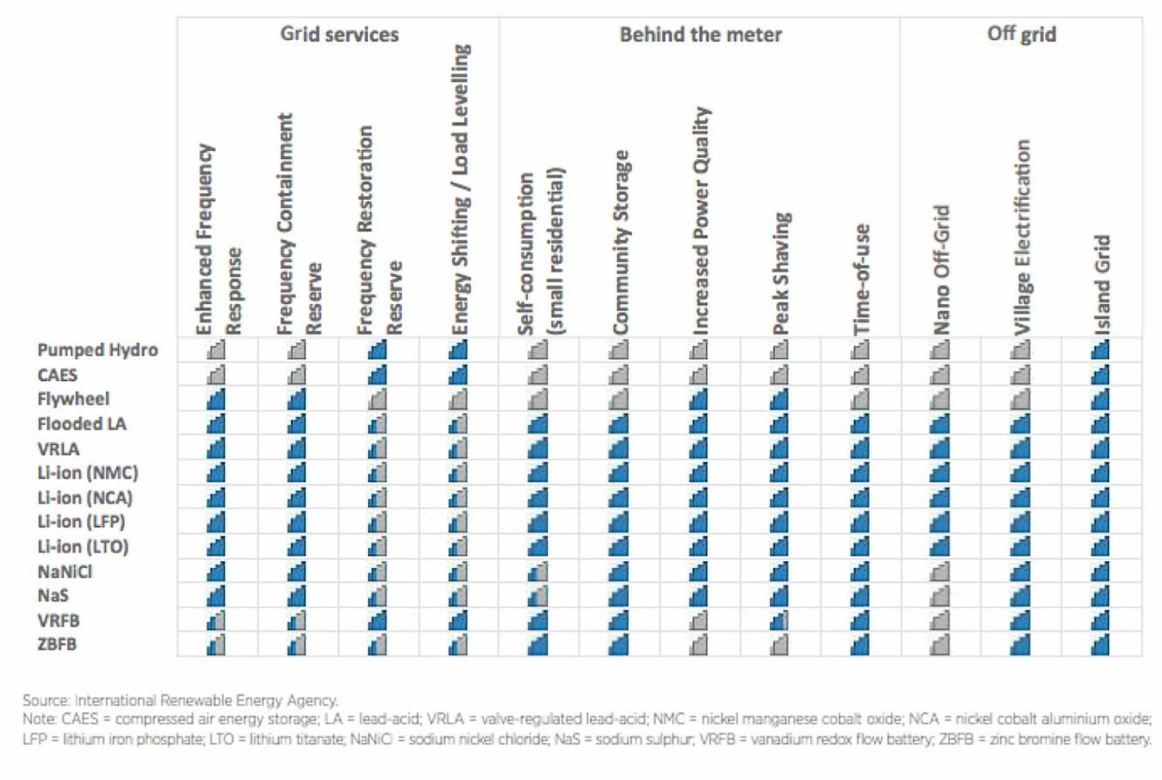


Figure 18 Suitability of storage technologies for different applications [13].

Both services, Enhanced Frequency response and Frequency Containment Reserve contribute to a smooth frequency signal to in-feed grid. Li-ion batteries could be combined with other high-power storage technologies, flywheels, to create cost-efficient hybrid battery systems that work well [13].

6 Review of regulations: energy markets

In this chapter, the regulations in the energy market will be analysed. This project is located in Spain. For the frequency data, it was not possible to obtain it through an open Spanish source. Nevertheless, in the case of energy markets there is available information in the website of REE [41].

6.1 Day ahead Market

The daily market shows the average, maximum and minimum price for one day. On the other hand, the day ahead market shows the exact €/MWh per every hour of a day (see Figure 19). For the approach of this project the day ahead market is the most interesting.

The required information is the electricity production price per hour since in the project we act as the electricity producers of the wind park, then the price should not contain access tolls or other relevant taxes.

The data needed is from VPSC (Voluntary Price for Small Customer). To select this data, it has been checked the website of REE through its information system: *e·sios* (System Operator Information System), that shows the exploitation of the Spanish Power System in real time [41].

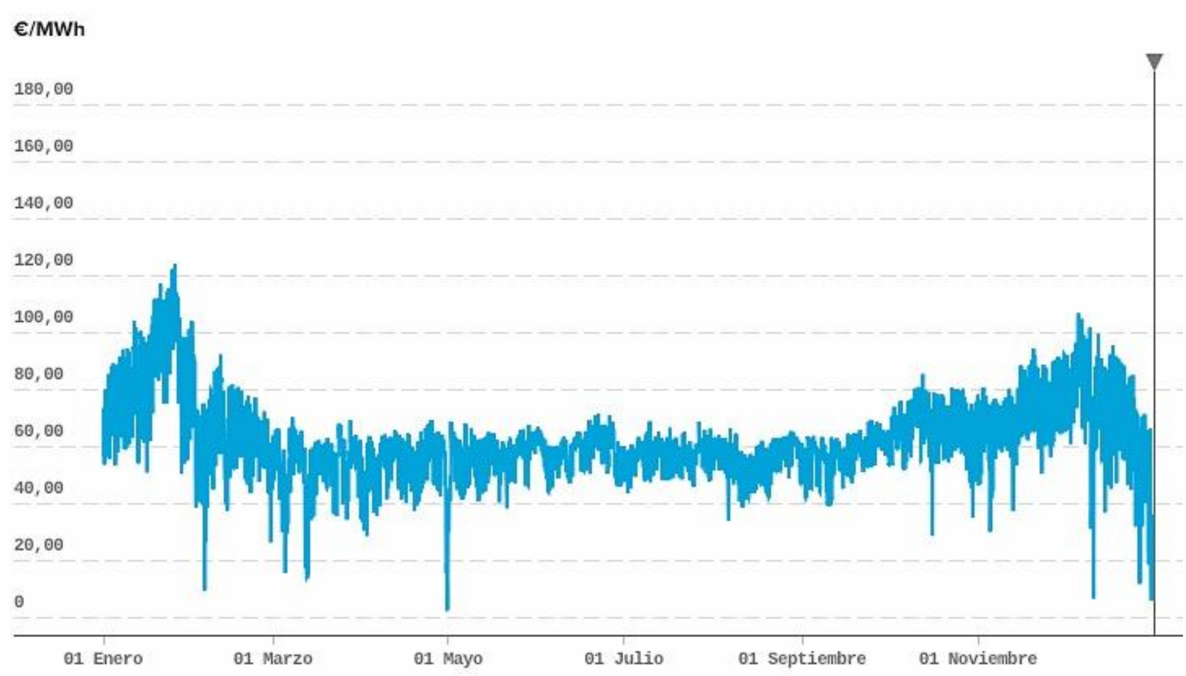


Figure 19 Day ahead market from 01-01-2017 at 00:00 to 31-12-2017 at 23:50, REE [41]

6.1.1 Cleaning data collection

For this project, the time step calculation is every 15 s then, since the data from REE is with an hour step it is needed to create a MATLAB code, Annex B, to create from an array of one hour another array with 15 s division of one hour (in total, 240 divisions per hour), as shown in Table 5.

Table 5 Example of the hour division in 15 s (own elaboration)

0:00:00	0:00:15	0:00:30	0:00:45	0:01:00	…	1:00:00

6.2 Primary frequency control payment structure

As well as there is a market for the day ahead production where all electricity producers are paid for the energy they are supplying into the grid, there are in the same way other payments involving the primary frequency control.

In the case of Spain, there are some grid service regulations that are paid by REE to the generator groups and others that are not. For example, primary frequency control in Spain is a mandatory service that needs to be followed by all synchronized generators groups (wind parks are not considered in this group [33]). Check next Figure 20 to see how different countries in Europe provide primary frequency control service:

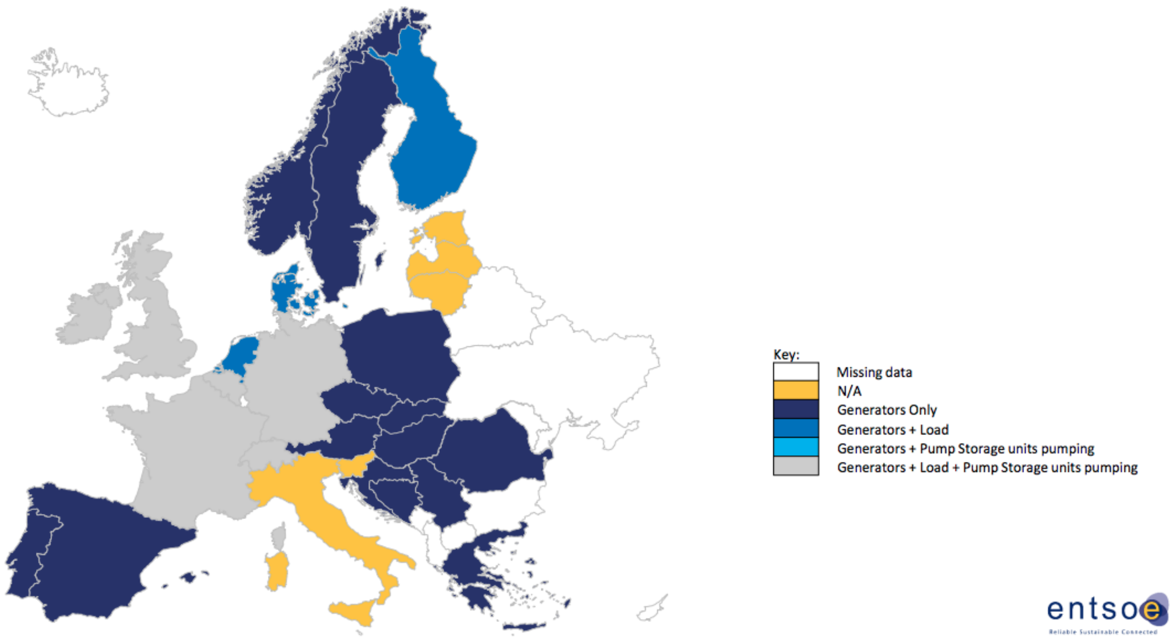


Figure 20 Primary frequency control - Capacity - Provider [42]

As it can be checked, there are several countries that have load or pump storage units that also help to provide this frequency service to the grid as well as there are many others that only provide the service as in Spain, through generator groups.

Nowadays, primary frequency control service is not paid by REE [37], see Figure 21 (line 2 “Regulacion Primaria” in Spanish).

Servicio	Definición	Carácter	Proveedores	Requerimientos Reserva
Reserva de potencia adicional a subir	Contratación y gestión de la reserva de potencia adicional a subir, necesaria con respecto a la disponible en el PDVP	Potestativo y remunerado, de oferta obligatoria	Grupos generadores térmicos habilitados por el OS	P.O.1.5
Regulación primaria	Actuación de los reguladores de velocidad de los grupos generadores ante variaciones de frecuencia (<30 seg)	Obligatorio y no remunerado	Todos los grupos generadores	Requerimientos ENTSO-E P.O.1.5
Regulación secundaria	Actuación de la RCP y de los AGC sobre los reguladores de grupos ante variaciones de frecuencia y del desvío respecto al programa con Francia (≤100 seg)	Potestativo y remunerado	Grupos generadores habilitados e integrados en zonas de regulación	P.O. 1.5
Regulación terciaria	Variación de potencia respecto a programa en tiempo no superior a 15 minutos que puede mantenerse hasta 2 horas	Potestativo y remunerado, de oferta obligatoria	Generadores y grupos de bombeo habilitados por el OS	P.O.1.5
Control de tensión (RdT)	Mantenimiento perfil tensiones nudos RdT: Tensión en los nudos de alta de las centrales de generación, Factores de potencia en nudos de distribución y consumo, Gestión de los elementos discretos	Parte obligatoria Parte potestativa (pendiente de implantación)	G: P≥30 MW C: s P≥15 MW Distribuidores Transportista	G: Reactiva ≥ +/- 15% Pn a tensión nominal C: Reactiva según periodos

Figure 21 Ancillary services by REE [43]

Ancillary services or adjustment markets are defined by REE as resolutions of technical constraints: << *[..] Adjustment service whose aim is to resolve the technical constraints of the system, by limiting and modifying, as deemed necessary, the production schedules of the power stations o pumped storage generation that allow technical constraints identified to be resolved with the lowest cost for the system, and the subsequent rebalancing of generation and demand to offset schedule modifications incorporated to resolve the identified technical constraints. >>*

On the other hand, this same service (primary frequency control) done by renewable generators (not synchronized groups) is paid in the UK by the National Grid due to the bad consequences that the group of generators have when they need to cut off their wind turbines in order to balance the grid and due to their big frequency fluctuations (as already checked in Figure 21) they need all groups providing this service.

As said before, Spain does not have its own grid code. It is assumed that hypothetically in the next years Spain will have one and hypothetically the REE will pay to the group of generators an amount for giving the primary frequency control service (because this is the tendency in the rest of European countries). Then, in order to take into account the service in the mathematical optimization of this project, it has been consulted the actual equations related to this service in the UK.

National Grid UK has been working in collaboration with wind park operators to develop a methodology that can be used to mitigate the risks associated with the existing response energy payment and the costs of the renewable energy certificate.

The payment in the National Grid UK are currently divided in [44], [45]:

1. Availability fee: Price per hour (€/h) for the hours a provider has offered availability of the service.
2. Nomination fee: There are specific rules for the renewable generators when low or high-frequency response and, the payment is made for each hour nominated (€/h)

$$Low\ Frequency\ response = Intraday\ Market * 0.75 \quad (6.2.1)$$

$$High\ Frequency\ response = Intraday\ Market * 1.25 \quad (6.2.2)$$

This equations (6.2.1) and (6.2.2) will be used in the MATLAB code (Annex B) to obtain the primary frequency control payment data for the GAMS optimization.

The availability fee has been checked from the Tender Report (May 2018). It is chosen a Tender with a battery that provides primary frequency control with a capacity of 2.4 MW. This battery has an availability fee of 42 £/h, that means, 47.8 €/h. This price is the payment the National grid does to the generator group every hour the battery is available to provide the energy it says (even if sometimes the energy is not needed to be supplied to the grid) [46].

The tender bid is done following the next steps:

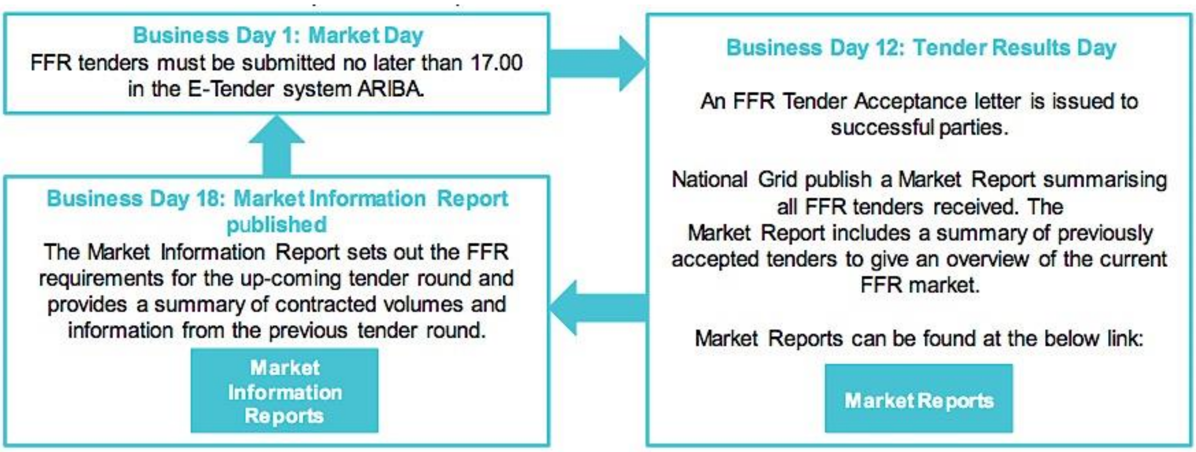


Figure 22 Tender process in National Grid for FFR [47]

The battery selected and the price that is going to be used for the calculations of this project are taken from a tender that has already passed all the steps shown above. The tender needs to start providing the service within a period of 6 months from the first available tender day.

What it can be assumed is that when Spain finally has its own grid code, hypothetically it could be used and followed this scheme as it does the National Grid UK (Figure 22) or even REE could create its own one taking into account different strategies for the Spanish national electricity market.

7 Wind park study

The goal of this project is not to develop a complete wind park, it is to study the possibility of the hybrid storage implementation helping the current wind parks to produce more, to have no curtailment and to help the grid when episodes of over-frequency or high-frequency occur without causing problems neither to the grid nor to the wind turbines.

To have a wind park study different steps needed to be done: First of all, it is studied the location site of the wind park taken into account different parameters and restrictions over Spain. Secondly it is used a website service to collect wind speed data for a complete year in the chosen location as well as a data treatment through a MATLAB code in order to get arrays of data with the dimension needed for every month of the year. Thirdly, it is chosen a wind power generator that is currently on the onshore market industry and has a data sheet already proven, since it was used in several wind parks over Spain and with its information the power generation of the wind park is finally calculated.

7.1 Location site of the wind park

To choose the site location of the wind park, several aspects have been considered:

1. Maturity of technology on the site – already existing wind parks
2. Annual average wind speed
3. High wind power density
4. Onsite natural parks – restrictions

Andalusia has been chosen for this project over the different communities of Spain because it is one of the top three autonomous communities with an already high power installed (3337.73 MW), it has a good wind category (large areas of annual wind speed > 6 m/s) and it has a high wind power density over the rest of communities. Please check the Figures 23, 24 and 25.

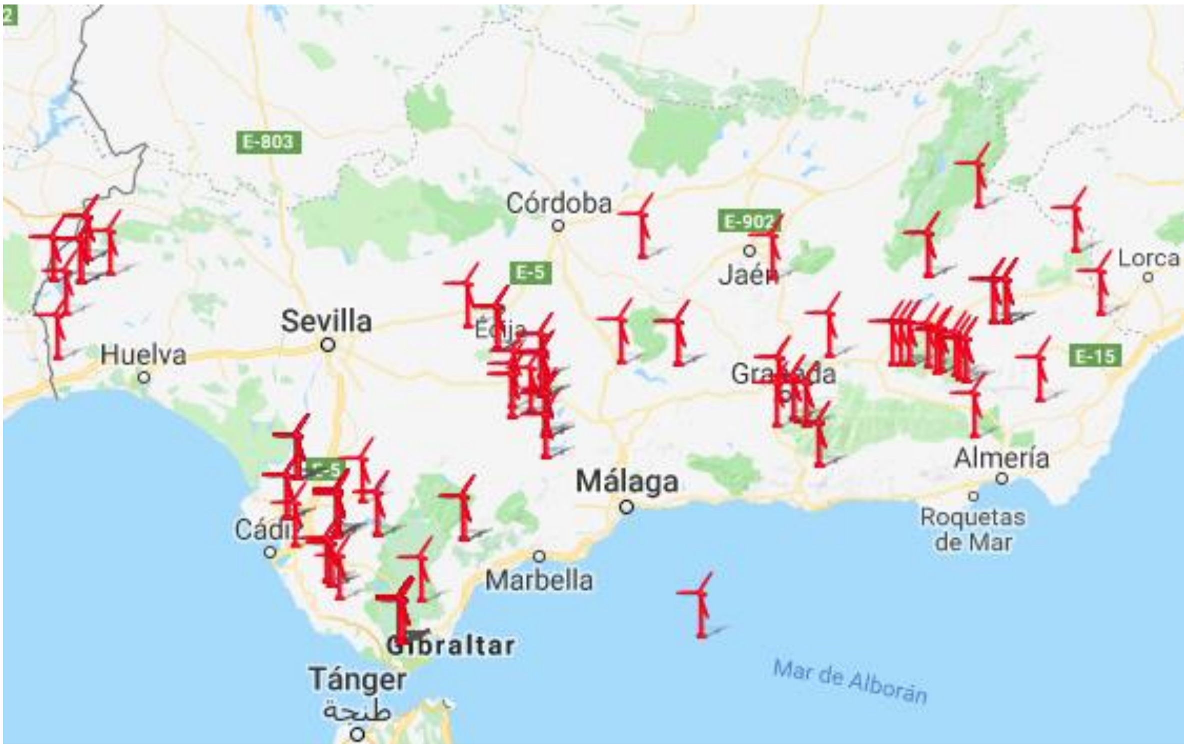


Figure 23 Wind parks over Andalusia [48] [49]

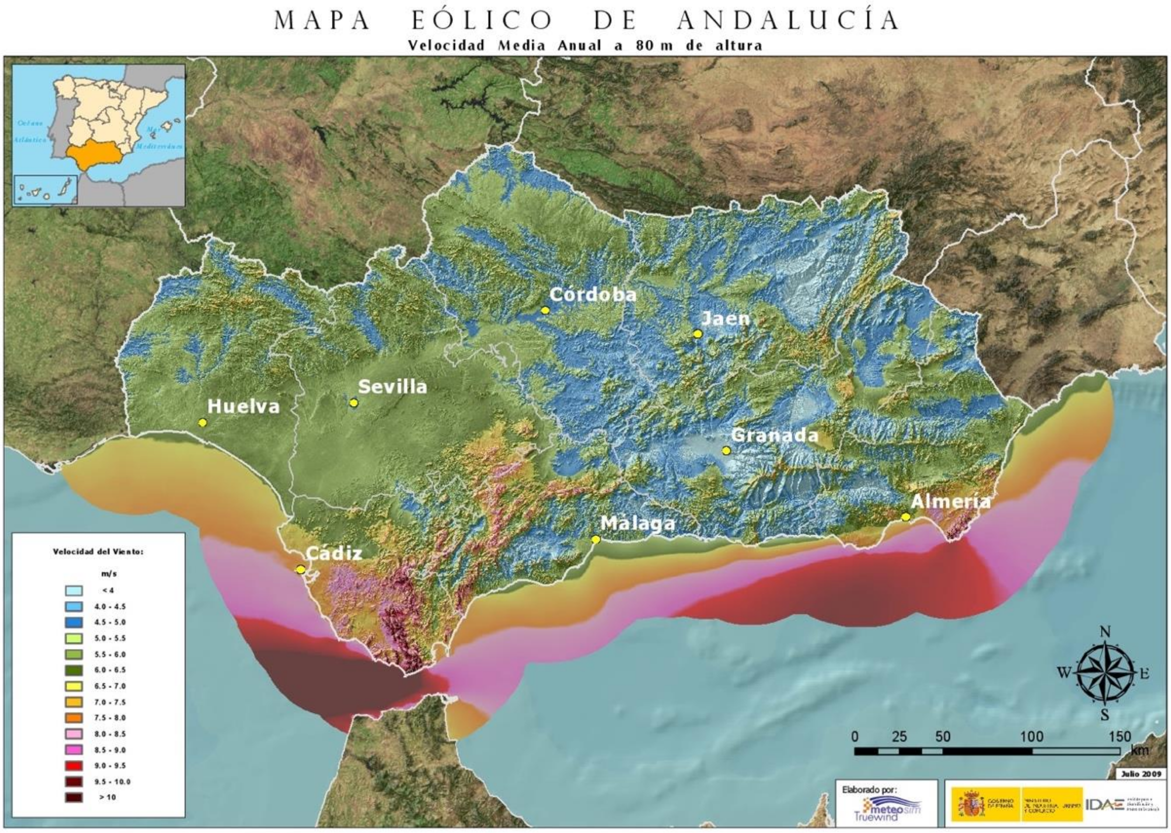


Figure 24 Andalusian wind map. Average wind speed at 80 m [50]

Figure 25 Spanish wind power density W/m² [50]

The "Atlas eólico" (wind atlas), elaborated by Meteosim Truewind in collaboration with IDAE (Institute for the diversification and Saving of Energy) that is a group assigned to the Ministry of Energy, Tourism and the digital Agenda through the Secretary of State for Energy, has been very useful in this study to get the best possible location.

As it can be checked in Figure 25, communities such as Galicia, Andalusia, or Canary Islands have a high wind power density with a total installed capacity of 3.337 GW in Andalusia, 3.314 GW in Galicia and few MW in Canary Islands (even though they have high power density) [49]. Finally, a province from Andalusia has been chosen due to the recorded history in wind parks that it already has over the over two communities. Inside Andalusia, the location chosen for the wind park is Puerto Real, Cádiz:

Latitude: 36.524353 and Longitude: -6.033672

In this location, there are already wind parks installed and in operation, Figure 26.

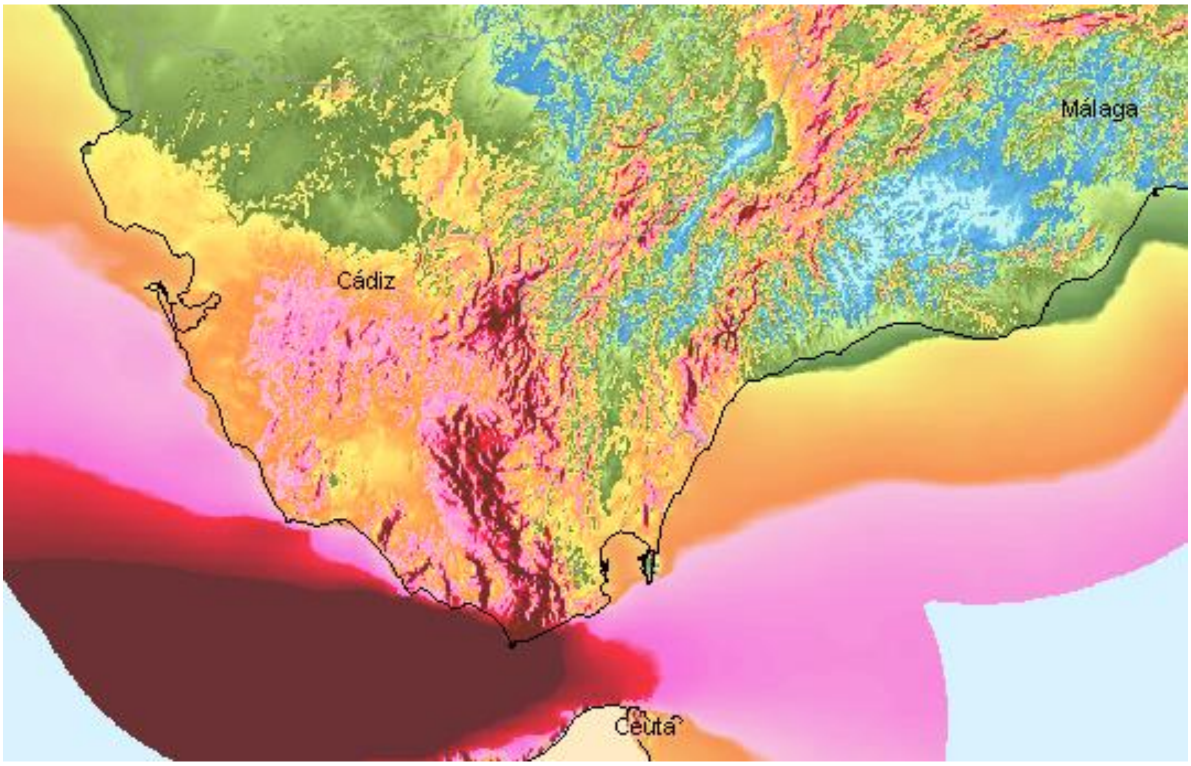


Figure 26 Cadiz IDAE map [50]

From IDAE website, it can be checked the Rugosity 0.1, Weibull *c* (9.49 m/s) and Weibull *k* (2.149 m/s). In the province of Cádiz there is a general good average wind speed (between 7.5 and 8.5) as it can be seen in the map below from IDEA [50].

The location has been chosen considering at the same time the IEC 61400 that is an International Standard published by the International Electrotechnical Commission (IEC) that sets international standards for the wind speeds. Check the Table 6 below to see the different wind classes [51]:

Table 6 Wind classes (IEC) [51]

Class	**Category**	**Wind Speed (m/s)**
IEC Class I	High wind speed	10
IEC Class II	Medium wind speed	8.5
IEC Class III	Low wind speed	7.5
IEC Class IV	low wind speed	6

Another requirement that needs to be checked in Spain is the existence of natural parks. There are no possibilities of setting a wind park inside a protected natural park. The following Figure 27 shows the natural parks in the community of Andalusia. As it shows, Cádiz has a large area around the natural park "*Doñana*" but it does not affect the location chosen for this project.

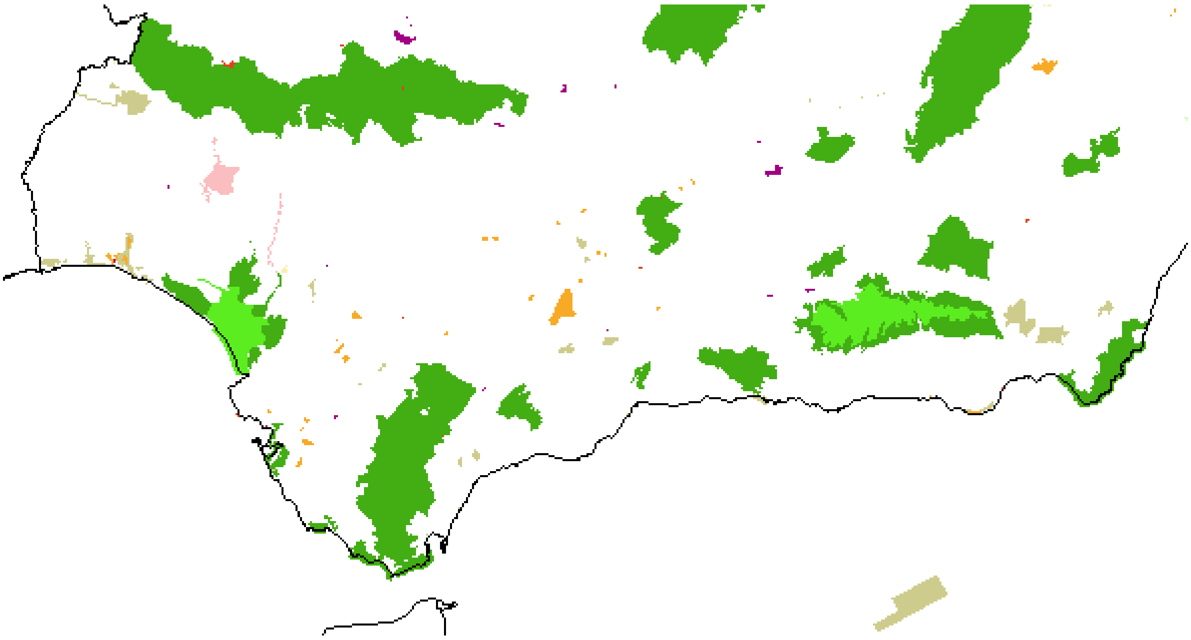


Figure 27 Andalusia Natural parks map [50]

Likewise, through the IDEA website it is possible to check the wind rose for the location chosen that should be uses to orientate the wind park and face it to the wind direction (see Figure 28).

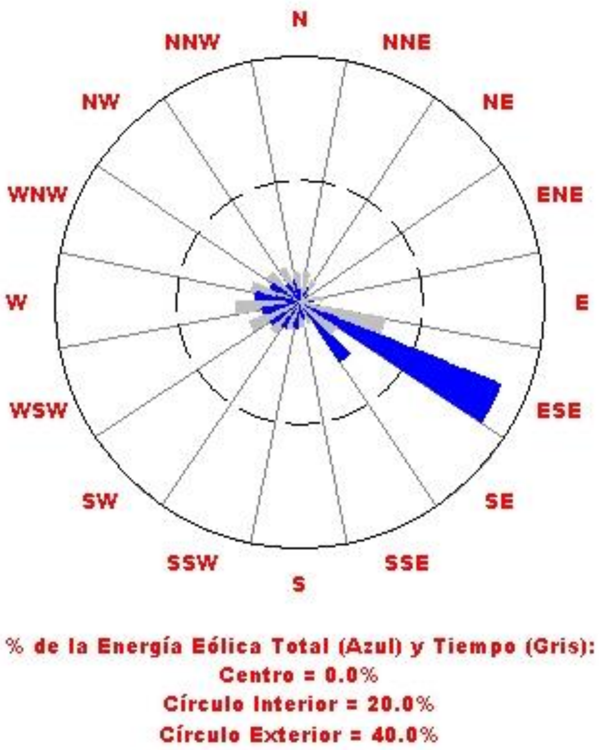


Figure 28 Wind rose in Puerto Real, Cadiz [50]

7.2 Data collection of the chosen location

To collect wind data of the chosen location, it has been used the web service of SODA Service that is an Intelligent System (SoDa-IS) that builds links to other resources that are located in various countries [52].

Right now, there are 6 different providers of this web service: NASA (National Aeronautics and Space Administration), ENTPE (École des ingénieurs de l'aménagement durable des territoires), NCEP (National Centers for Environmental Prediction), METEOTEST, MINES ParisTech, ISAC (Institute of Atmospheric Sciences and Climate). Linking the information of all of them, the SODA website service creates a final data set.

Data from the SODA Service is realistic enough for free-open database standards.

In this project, the annual data for wind speed (m/s) in the exact location chosen Puerto Real, Cádiz (latitude: 36.524353, longitude: -6.033672) has been taken minute by minute for all months of 2017 as one can check in Figure 29.

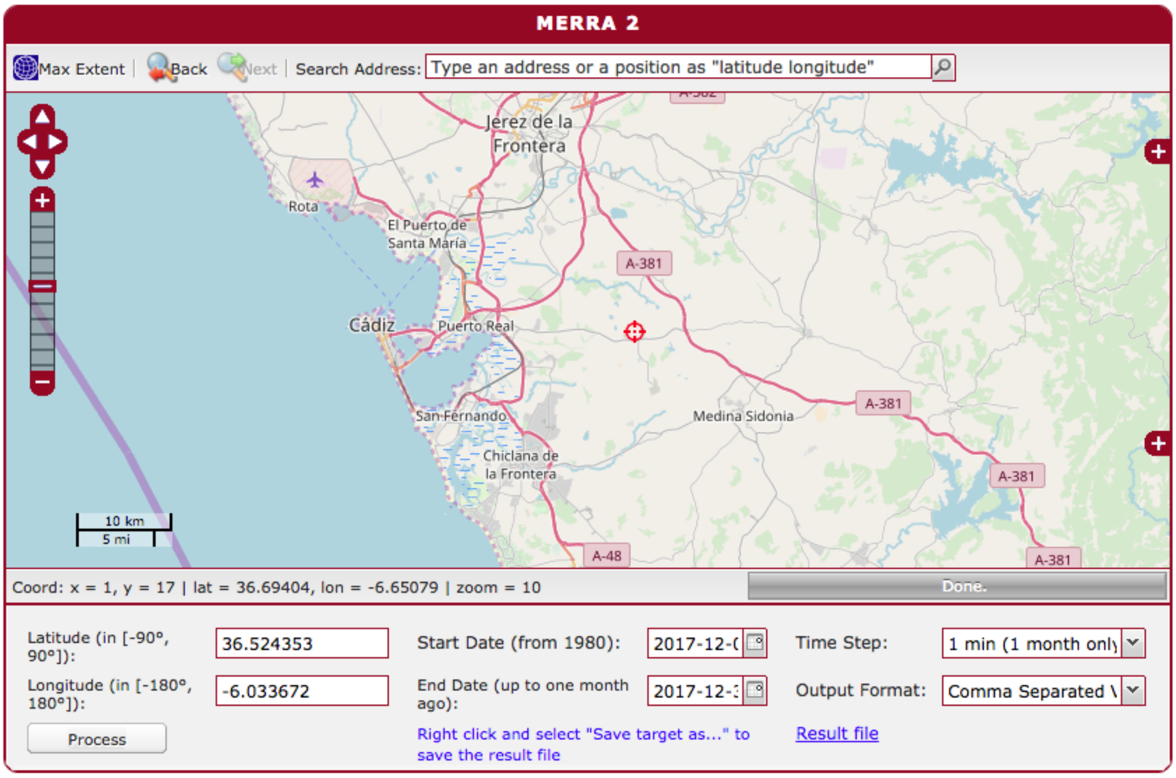


Figure 29 Soda-Pro Software [52]

7.2.1 Cleaning data collection

Once the wind speed was found for a complete year, the data was shaped to match with the frequency data of the grid in time step. The SODA servers give wind speed information minute by minute and we have our time integration for the model in second (every 15 s) to be more accurate.

A MATLAB code has been created to do an interpolation between two different minutes extracting from them three more data points with an interval of 15 s. Check Annex B and Table 7.

Table 7 Example of the wind speed interpolation in 15 s (own elaboration)

1'	1.25'	1.5'	1.75'	**2'**

7.3 Wind park calculation for the location chosen

Once the wind speed is obtained and treated, the next step is to calculate the power generation. To do so, a wind generator is needed.

The wind generator that has been chosen in this project is the aero generator Gamesa G128 – 4.5 MW that is a PMSG (permanent magnet synchronous generator) with full converter technology (scheme on Figure 30).

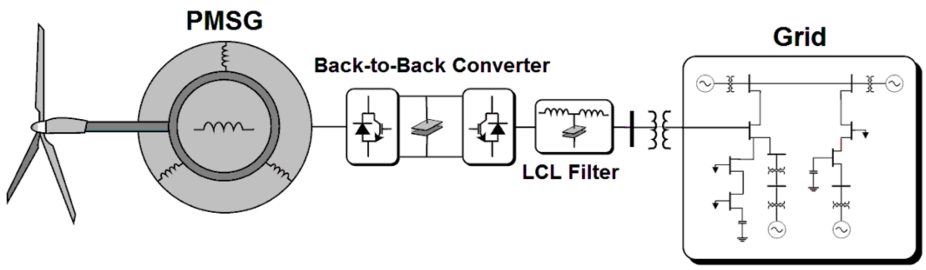


Figure 30 Permanent Magnet Synchronous Generator scheme [53]

For a PMGS type, the gearbox can be omitted, and all the difficulties that it presents can be eliminated. The wind energy collected from the wind turbine is sent to the generator. There, a PWM pulse width modulation converter controls the rotational speed of the PMSG. Through an AC/DC generator side converter and a DC/AC grid side inverter, the output power of the PMSG is in-feed to the grid.

Gamesa has a long trajectory in the wind field designing, manufacturing and validating its products in Spain [54]. Recently, Siemens Gamesa has been created to boost the renewables all over the world [55].

In the wind market, it is possible to find the aero generator Gamesa G128 – 4.5 MW (see Table 8). This generator has been chosen over others because it has been proven by several wind parks in Spain. There is plenty of information about how it works and its power curve is also available in the wind-turbine-models or the wind power websites [56], [57].

Table 8 Main Characteristics of Gamesa G128 - 4.5 MW aero generator [56] [57]

Characteristic	**Unit**
Rated Power	4500 kW
Cut-in wind speed	2 m/s
Rated wind speed	12 m/s
Cut-out wind speed	27 m/s
Rotor type	PMSG
Rotor diameter	128 m
Swept area	12868 m^2
Power density	349.7 W/m^2
Nº of blades	3
Generator type	Synchronous
Max speed generator	448 rad/min
Hub height	81/120/140 m
Rotor + Hub weight	83.9 tonnes

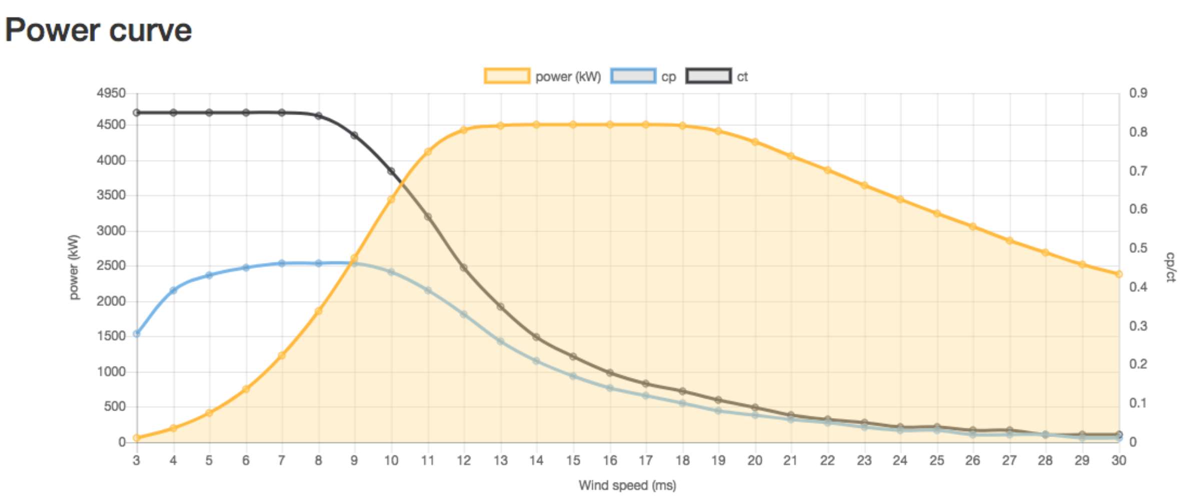


Figure 31 Power Curve Gamesa G128-4.5 MW [56]

From the power curve of the generator (Figure 31), the C_t and the C_p are available data for the different wind speeds. The C_p curve is going to be used for every wind speed variation from last section 4.2, to get the exact power generation over the complete year.

To do so, again, it is created a MATLAB code. Please check (Annex B).

Having this proven generator, every wind speed has a proven historical data of C_p, which helps this project to have a more realistic power generation calculation. Check the equation of Power Generation, equation (7.3.1) that is used in the MATLAB code.

$$Power\ Generation = \frac{1}{2}\rho_{air} A v^3 C_p \qquad (7.3.1)$$

Already existing wind parks in the area of the chosen location can take advantage of the findings of this project.

7.4 Results of the wind park generation

The study case is the hybrid combination of a power pack battery storage system, a flywheel storage system and a wind park.

First, the results of the MATLAB wind park simulation are shown. Straightaway, results from the GAMS simulation are shown: the combination between the wind park and the lithium-ion batteries and last the combination of the wind park with the hybrid system (lithium-ion batteries and the flywheel).

7.5 Results of the wind park generation in MATLAB

After a MATLAB code (Annex B) created to obtain the power generation of the wind park. Here two different months with different wind speed fluctuation are shown through Figure 32 and 33.

Figure 32 Power curve WT in March (own elaboration)

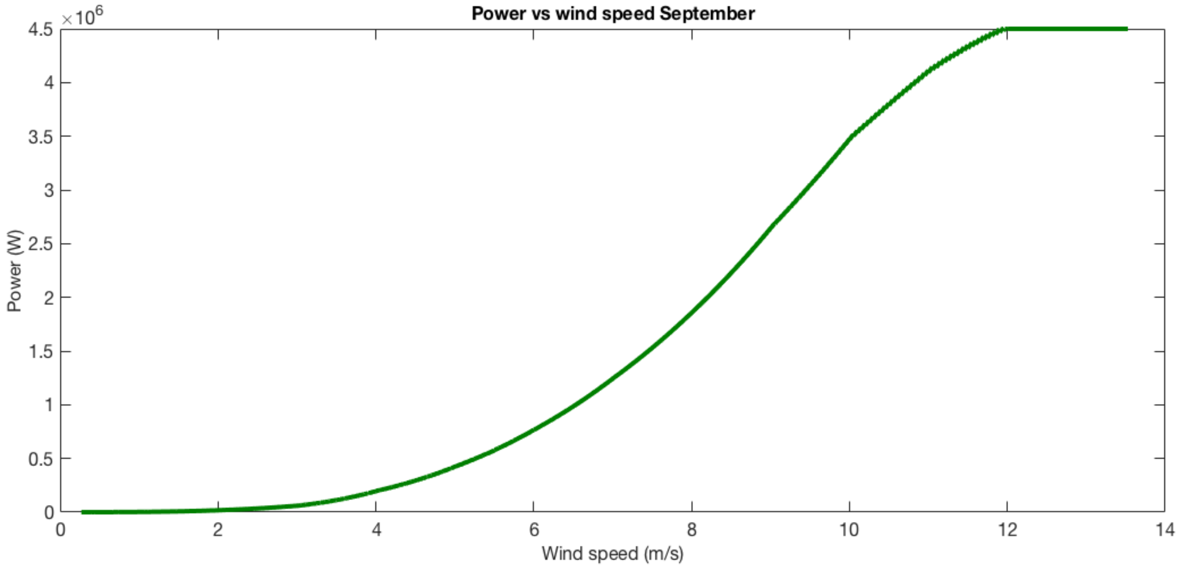


Figure 33 Power curve WT in September (own elaboration)

The variation of the wind speed in the location chosen is diverse over all months of the year. In some months like March it is possible to reach 26 m/s and have a high average of wind speed. Other months such as September, the wind speed has an almost maximum of 14 m/s and their average wind speed is low in comparison with other months as can be checked in Table 9.

In addition, it can be checked that the power has been cut at 4.5 MW since it is the maximum power that the wind turbine can support without suffering damages.

The wind speed is affecting the final power that the wind park will generate. Doing a separation of all the graphs it can be checked how much power they are generating every month. As the wind park is not going to have only one turbine, in the simulation of the MATLAB code (Annex

B) the aggregated model is used. It means that the power generated by one Gamesa wind turbine has been multiplied by 20 (to complete a wind park). Thus, the total power installed in the wind park is 90 MW.

The number of wind turbines has been decided to be 20 because there are already other wind parks in Puerto Real, Cádiz with 14 and 17 turbines respectively [58], [59]. The final power generation results from the 20 turbines wind park are shown in Table 9.

Table 9 Energy generated for the wind park per month (own elaboration)

Months	**Average wind speed (m/s)**	**Total Energy (MWh)**
January	7.391	26700
February	8.013	27000
March	8.326	33200
April	9.378	32000
May	8.284	31100
June	7.845	30300
July	6.442	20300
August	6.167	19800
September	5.852	16100
October	6.937	21200
November	6.726	19900
December	7.707	27700

The average wind speed over a year is 7.422 m/s. Taken a month that has an average wind speed of 7.391 m/s (January), the power fluctuation with wind speed changing every 15 s during that month is shown in Figure 34.

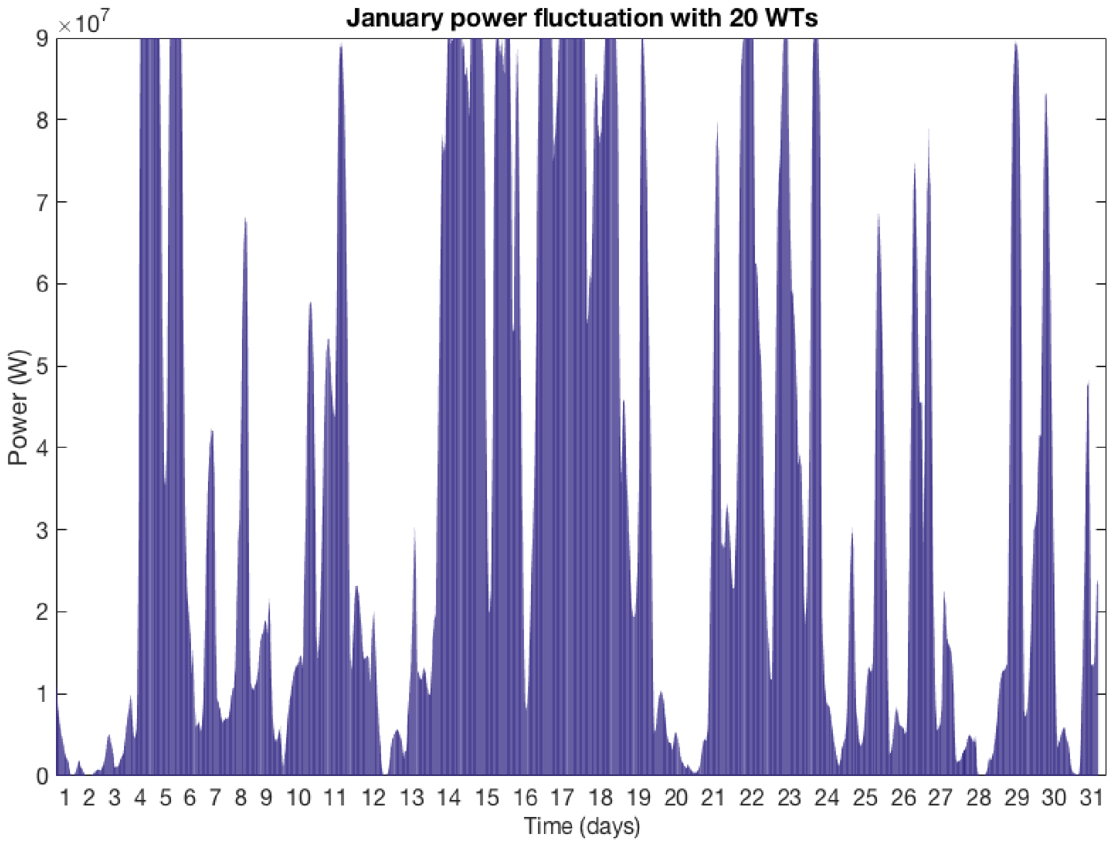


Figure 34 Power fluctuation in January due to wind turbine variations (own elaboration)

It is remarkable how the power generated by the wind turbines is continuously changing due to wind speed variations.

8 Mathematical optimization problem

The mathematical optimization problem through GAMS software maximizes the investment cost of the WP with the respective ESS, sizes the ESS and gives the net income of the wind park during its lifetime.

In the following subsections, variables, parameters and equations used in GAMS are defined.

8.1 Variables of the optimization problem

Gams parameters (For every of the case studies, the parameters of the ESS will change)

ESS parameters

α_{low} Lowest limit of charge (that depends of the ESS type) (%)

α_{high} Highest limit of charge (that depends of the ESS type) (%)

γ Percentage of losses of the energy stored (%)

C_{ESS} Capital cost of the ESS (€)

η_{+} Charging efficiency of the ESS (%)

η_{-} Discharging efficiency of the ESS (%)

λ_{EpsP} Capital cost of ESS on power basis (€/MW)

λ_{EpsS} Capital cost of ESS on an energy basis (€/MWh)

λ_{Dis} Degradation cost of the ESS (€/MWh)

WT parameters

E_{max} WT generation (MWh) – Parameter calculation in MATLAB code (Annex B)

Frequency parameters

$Eu_{fr,t}$ Energy needed to be supplied for frequency variations in the grid (frequency response) (MWh) – Parameter calculation in MATLAB code (Annex B)

$Eu_{fr,Hz,lim}$ Energy needed to be supplied for the max frequency variation in the grid (frequency response at -0.5 Hz from nominal frequency) (MWh) – Parameter calculation in MATLAB code (Annex B)

$\lambda_{ufr,t}$ Primary frequency control price (€/MWh) – Parameter calculation in MATLAB code (Annex B)

Market price parameters

$\lambda_{m,t}$ Day ahead market price (€/MWh) – Parameter calculation in MATLAB code (Annex B)

Variables are optimized and solved in the mathematical problem in GAMS.

ESS variables

EpsP ESS power (MW)

EpsS ESS energy capacity (MWh)

C_{s} ESS capital cost (€)

C_{deg} ESS capital cost due to degradation with time (€)

$\varepsilon_{loss\_comEpsP}$ Energy sent to ESS to cover the ESS losses (MWh)

EpsS_{in} Energy entering to the ESS due to primary frequency control (high-frequency episodes) (MWh)

EpsS_{out}	Energy released from the ESS due to primary frequency control (low-frequency episodes) (MWh)
EpsS_{loss}	Energy loss from ESS due to primary frequency control (MWh)
EpsS_{C}	Charge in ESS at time t in kWh

Frequency variables

Eps_{ufr}	Frequency response provided at time t in MWh

WT variables

W_{out}	Energy discharged from the wind turbines at time t in kWh for low-frequency response (MWh)
W_{in}	Energy “charged” (reserve) from the wind turbines at time t in kWh for high-frequency response (MWh)
$\mathrm{W}_{reserve}$	Reserve provided by the wind turbines at time t in kWh.
W_{gen}	Balance in wind generation that affect the amount of energy sold (MWh)

Market price variables

$I_{m,t}$	Income from day ahead market at time t (€)
$I_{fr,t}$	Income from primary frequency control provision

General balance variables

Θ_t	Energy sold to the grid (MWh)
Z	Objective Function (€)

8.2 General constraints

- Global balances: To calculate the energy sold to the grid in the range of hours specified in the simulation and to calculate the energy exchanged to the grid due to frequency fluctuations
- Wind Turbine balances: To calculate the maximum energy the WT can provide for frequency response and to calculate the energy generated by the WT any time.
- Storage device balances: to restrict the charge, to balance the storage system, and to estimate the energy losses in the ESS.

8.3 Objective function of the optimization problem

Some of the GAMS equations explained next, have been reused from Johnson L et al. [19] paper.

The objective function is the total net income that the wind park will generate over its lifetime with a ESS. It is defined considering the total electricity sold, the cost of the ESS and its losses during charge/discharge and degradation and the incomes from the primary frequency control.

- The Electricity sold at time t is defined in Eq. (8.3.1),

$$I_{m,t} = \lambda_{m,t}\Theta_t \quad (8.3.1)$$

- The capital cost due to the ESS is defined in Eq. (8.3.2),

$$C_s = \lambda_{EpsP}\mathrm{EpsP} + \lambda_{EpsS}EpsS \quad (8.3.2)$$

- The capital cost due to ESS degradation is defined in Eq. (8.3.3) at any t, 15 is the lifetime in years,

$$C_{deg} = 365 * 15 * \sum (\mathrm{EpsS}_{loss} + \mathrm{EpsS}_{out})\lambda_{Dis} \quad (8.3.3)$$

- Income from primary frequency control provision is defined in Eq. (8.3.4), u is just a positive 1 when frequency response required is positive,

$$I_{fr,t} = u\frac{\lambda_{ufr,t}}{\mathrm{Eps}_{ufr}} - (1-u)\frac{\lambda_{ufr,t}}{\mathrm{Eps}_{ufr}} \quad (8.3.4)$$

The final objective is defined in Eq. (8.3.5),

$$Z = -\mathrm{C}_s + \mathrm{C}_{deg} + I_{m,t} + I_{fr,t} \quad (8.3.5)$$

Other important equations for the optimization problem

The energy generated by the WT are defined in Eq. (8.3.6) and (8.3.7),

$$\mathrm{W}_{gen} = \mathrm{E}_{max} - W_{reserve} - \mathrm{W}_{out} \quad (8.3.6)$$

$$\frac{\mathrm{W}_{reserve}}{\mathrm{E}_{max}}(1) - \frac{\mathrm{W}_{reserve}}{\mathrm{E}_{max}}(t) = \frac{\mathrm{W}_{out}}{\mathrm{E}_{max}}(t) - \frac{\mathrm{W}_{in}}{\mathrm{E}_{max}}(t) \quad (8.3.7)$$

The grid load balance is defined in Eq. (8.3.8), as the energy sold to the grid without counting the primary frequency control service,

$$\Theta_t = W_{gen,t} - \frac{\varepsilon_{loss_{comEpsP}}}{\eta_+} \quad (8.3.8)$$

The frequency response balance is defined in Eq. (8.3.9), as the energy exchanged to provide the frequency response service,

$$\mathrm{Eps}_{ufr} = \mathrm{EpsS}_{in} + \mathrm{EpsS}_{out}\,\eta_{-} - W_{out} - \mathrm{W}_{in} \quad (8.3.9)$$

Storage equations are defined in Eq. (8.3.10),

$$\mathrm{EpsS}_C(t) - \mathrm{EpsS}_C(t-1) = \varepsilon_{loss_{comEpsP}} + \mathrm{EpsS}_{in} - \mathrm{EpsS}_{loss} + \mathrm{EpsS}_{out} \quad (8.3.10)$$

The maximum and minimum charge stored follow the next Eq. (8.3.11) and (8.3.12),

$$\mathrm{EpsS}_{Cmax} \leq \alpha_{high} EpsS \quad (8.3.11)$$

$$\mathrm{EpsS}_{Cmin} \geq \alpha_{low} EpsS \quad (8.3.12)$$

The power storage restrictions are defined in Eq. (8.3.13) and (8.3.14), where Thh is one hour in minutes and Ts the time step of the data provided for the simulation in minutes,

$$\mathrm{EpsP} \geq \varepsilon_{loss_{comEpsP}} + \mathrm{EpsS}_{in} \frac{Thh}{Ts} \quad (8.3.13)$$

$$\mathrm{EpsP} \geq \mathrm{EpsS}_{loss} + \mathrm{EpsS}_{in} \frac{Thh}{Ts} \quad (8.3.14)$$

Non-negativity of variables

Variables that cannot be negative: EpsP, EpsS, $\varepsilon_{loss_{comEpsP}}$, EpsS_{in}, EpsS_{out}, $\mathrm{W}_{reserve}$ and W_{in}.

9 Study Cases

All previous sections have been studied to finally define the study cases for this project. Summarizing, grid regulations taken from the European grid code, market day ahead analysis from Spain (REE) plus primary frequency control payment from the UK (National Grid) and the wind park calculations with MATLAB software, allowed us to make a mathematical optimization problem through GAMS software which focus on maximizing the investment cost of the different study cases, the size of the ESS (if needed) and the income of the wind park during 15 years of lifetime.

There are 4 study cases simulated with different mathematical optimization models in GAMS.

1. Wind park optimization with no ESS
2. Wind park optimization with a pack of lithium-ion batteries (BESS)
3. Wind park optimization with a FESS
4. Wind park optimization with the hybrid ESS (BESS + FESS)

To complete the optimization simulation for every of the cases there have been adopted some GAMS equations from a Johnson L et al. [19] paper, as said before, as well as new equations were created. Every case has different restrictions that are commented in the respective subsections of this Section 9. Because of that the simulation models are general and modifiable depending on the kind of ESS solution and energy market restrictions.

The simulations are done for an average day, on wind speed perspective, and for a high wind speed fluctuation day, 31st of January and 3rd of March respectively.

Figure 35 shows the wind speed fluctuation on March and how the line of the 3rd day of the month fluctuates the most (all months have been compared using the *variance* command from MATLAB). The day 3rd of March (gross purple line) is the worst-case scenario.

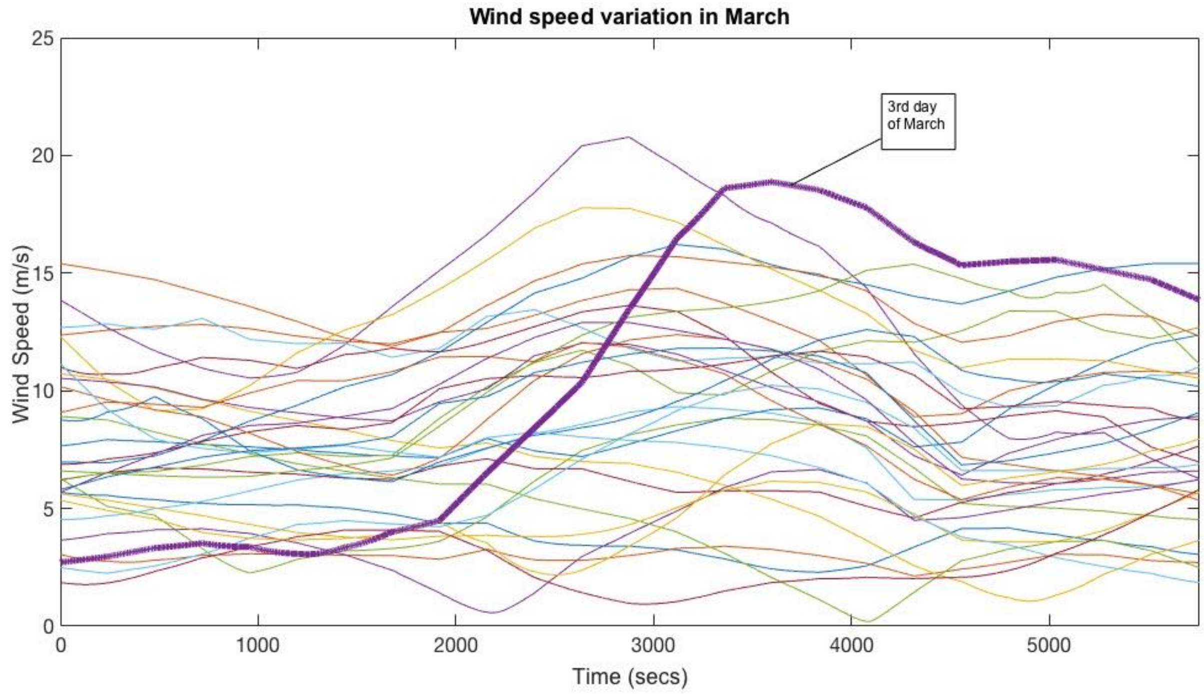


Figure 35 Wind speed values in March for every day of the month (own elaboration)

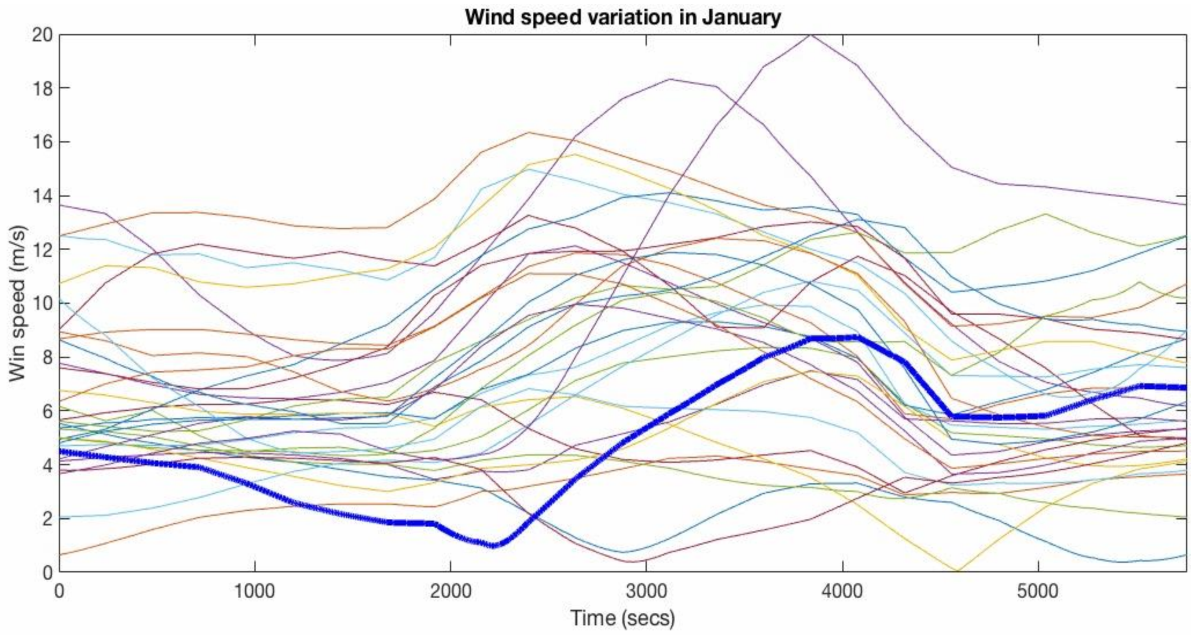


Figure 36 Wind speed values in January for every day of the month (own elaboration)

On the contrary, Figure 36 shows that the 31st of January (gross blue line) has a low wind speed variation. This scenario has no remarkable wind speed variations.

9.1 Study cases optimization results

9.1.1 Wind park optimization with no ESS

In this case study, the WTs are the ones providing the primary frequency control. To make this first simulation, we needed GAMS not to take into account any ESS. Then, the logical restriction was to settle a high price for the λ_{EpsP} and λ_{EpsS} (capital cost of ESS on power basis, in €/MW). This way, GAMS is not willing to use a battery for the optimization of the mathematical problem.

In addition, in this first optimization the objective function has been changed, Eq. (9.1.1.1), from before since there is no ESS contemplated.

$$Z = C_{deg} + I_{m,t} + I_{fr,t} \quad (9.1.1.1)$$

The energy generated by the wind park during low-frequency or high-frequency episodes will be controlled by the control drop through the power electronics of the aero generator Gamesa G128 – 4.5 MW because it is a PMSG (Type 4), providing this way the primary frequency control service.

Furthermore, due to the lack of an ESS, the aero generators will be operating at deloaded mode. This means that the highest power generation capacity will be 90 %. There is a 10 % of “power reserve” in case the grid needs it for support. What’s more, is that when there is a high-frequency episode, for example 50.02 Hz, the power electronics of the aero generator thanks to the drop control presented in Section 5.2, will make them operate at 88%, it means that there will be a 12 % of power capacity lost/not used, however the primary frequency control will be carried out. When there is an under-frequency episode, the aero generators will have the 10 % “reserve” ready to feed the grid (power electronics will make the rotor rotate at higher speed if wind conditions allow to do so).

The mathematical optimization was done for the 31st of January. The worst-case scenario has not been simulated because the aim of this result is to check that the system is working well providing primary frequency control through the WTs as can be checked in Figure 37.

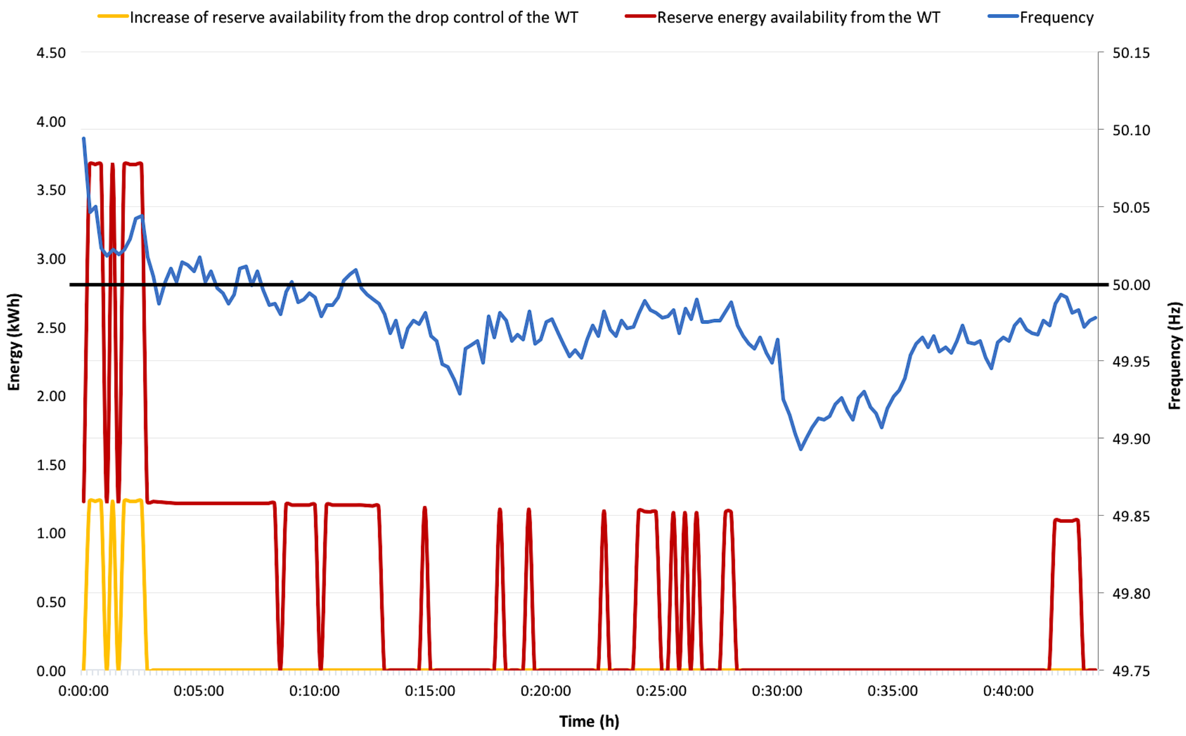


Figure 37 WT energy behavior with drop control (own elaboration)

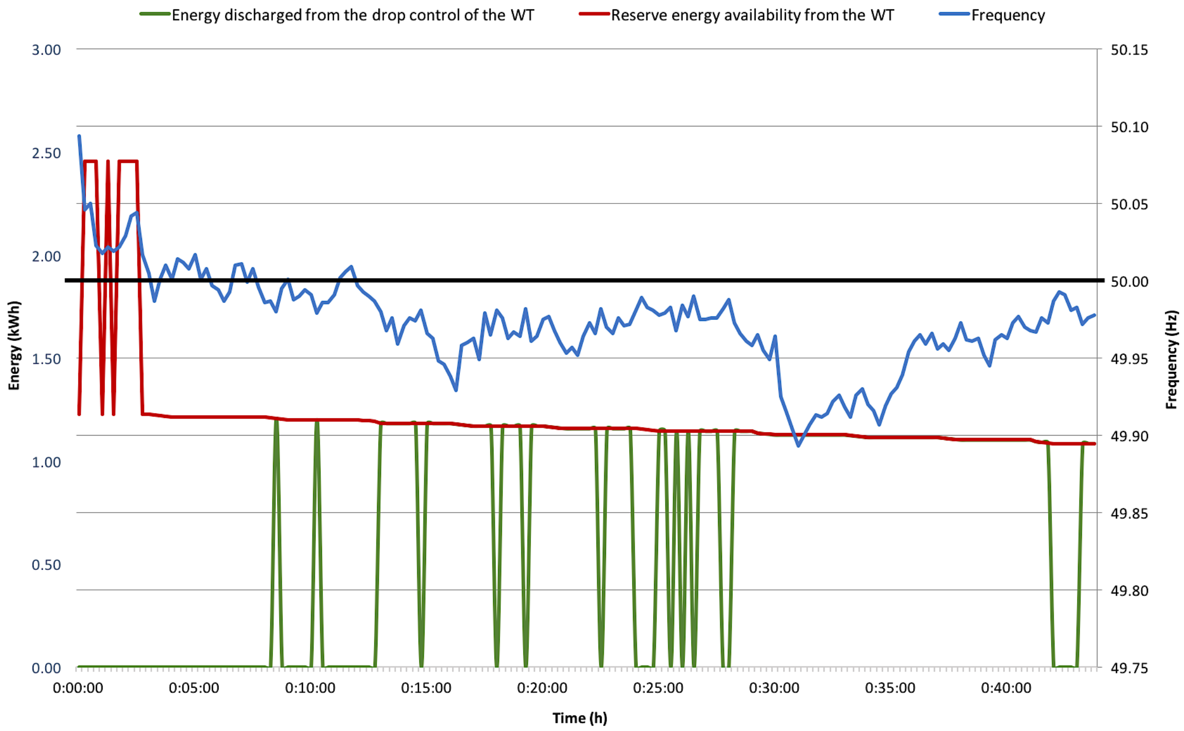


Figure 38 WT energy behavior with droop control 2 (own elaboration)

These two Figures 37 and 38, show that for low-frequency episodes, there is not an increase of the reserve that the WT should provide, that is logical because when low-frequency, what the WT must do is to discharge more energy to the grid. When a high-frequency episode occurs, the reserve increases and as previously explained, it means that instead of operating at 90 % the WT will operate at 88 % or even lees depending on how much the frequency drops.

The net income from a current WP in Spain with no ESS is simulated for the worst-case scenario (3rd of March) should approximately be what we have as results:

Final net income (15 years of operation), $I_{m,t} = 3.291$ x10^8 €

Total energy sold to the grid, $\Theta_t = 1.206$ x10^6 MWh

While low and high-frequency events the WTs have “charge” and “discharge” from its power electronics as follows for primary frequency control, $W_{in} = 22308.15$ MWh, $W_{out} = 25241.44$ MWh.

9.1.2 Wind park optimization with BESS

In this study case, the BESS together with the WTs carry out the primary frequency control. There are 2 scenarios for this Study case: Scenario 1 for 31st of January and Scenario 2 for 3rd of March.

The parameters used for this case study are values from a NMC lithium-ion battery. It has been chosen from a South Korean company (SK Innovation Co). Data-sheet is confidential, but some characteristics are listed for this project understanding: High cyclability (>5500), 95% efficiency, low environmental impact (model composition of 80% nickel, 10% cobalt and 10% manganese), 15 years lifetime. There was an offered price of 195 €/kWh.

$\alpha_{low} = 10\ \%$

$\alpha_{high} = 100\ \%$

$\gamma = 3\ \%$

$\eta_{+} = 95\ \%$

$\eta_{-} = 95\ \%$

$\lambda_{EpsP} = 150$ €/kW

$\lambda_{EpsS} = 195$ €/kWh

$\lambda_{Dis} = 0.05$ €/kWh

The discharging cost (€/MWh) and the price of the converter (€/kW) has been taken from previous experiences in the department.

In this study case, the mathematical optimization was done for a wind park and a NMC lithium-ion battery energy storage system for the Scenario 1 data collection. Figure 39, shows the behaviour during one hour of the day.

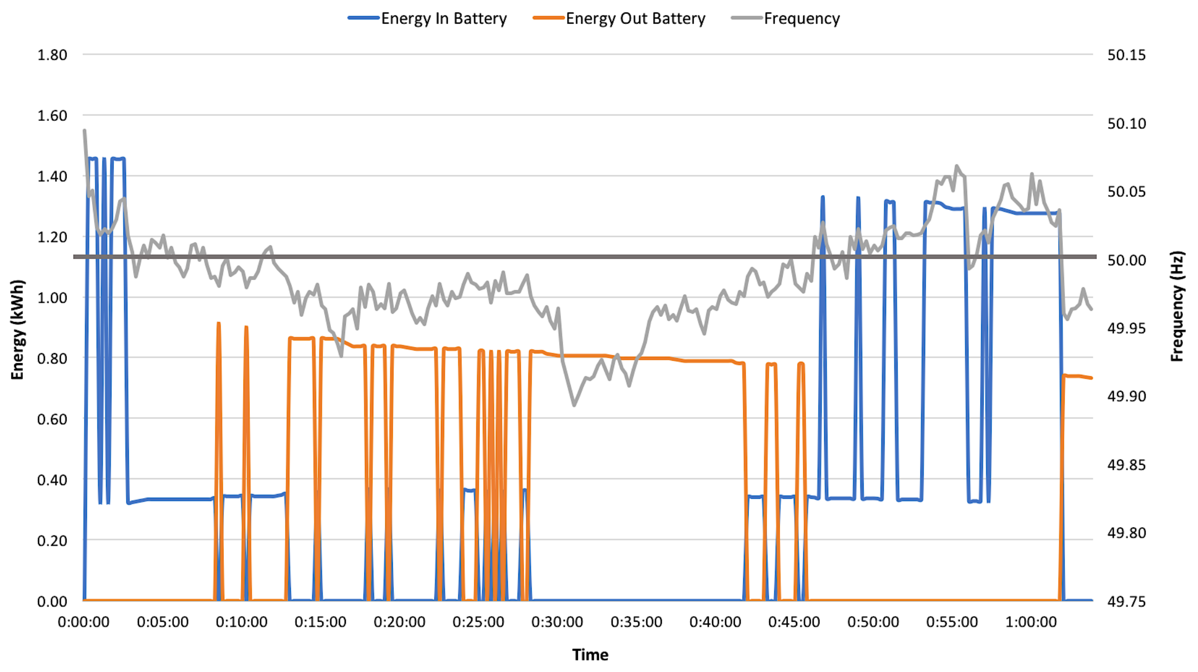


Figure 39 BESS behavior vs frequency variation (own elaboration)

Figure 39 shows that during high-frequency episodes the battery charges, since the grid does not need to be fed and during low-frequency episodes it is noticed how the battery discharges.

Moreover, when 50 Hz, it happens that the BESS also presents a nominal charge of 0.34 kWh. For the optimization, also variations of those 50 Hz up to 50.02 or 49.98 Hz are simulated and obtained same results 0.34 kWh, this happens because 50.02 and 49.98 Hz are within the dead band range (no exchange of energy). The small amount of energy 0.34 kWh is exchanged to compensate the losses caused from the self-discharge of the battery (in the parameters, γ is settled at 3 %).

Size Results are shown in Table 10.

Table 10 BESS size results (own elaboration)

Days for the Scenarios 1, 2	BESS Power (MW)	BESS Energy Capacity (MWh)
31st of January	4.79	6.18
3rd of March	9.07	11.54

The net income from a WP with a BESS providing primary frequency control is simulated for both scenarios should approximately be what we have as results:

Table 11 Results for the two scenarios of the second study case (own elaboration)

Days for the Scenarios 1 and 2	Net income (€)	Total Energy sold to the grid (MWh)	Charge Balance (MWh)
31st of January	1.682×10^{8}	3.718×10^{5}	19.635×10^{6}
3rd of March	3.426×10^{8}	1.338×10^{6}	52.105×10^{6}

The high growth in the net income is basically due to the total energy sold to the grid and the size of the BESS. As checked before in Figures 35 and 36 the two days chosen have strong differences in wind speed variations. When for 31st of January the wind speed average is low, max 10 m/s, for the 3rd of March it rises up to 20 m/s. In other words, the maximum power point of the WT 31st of January is not reached while it is for the 3rd of March. The power generation is much higher (up to 4.5 MW – WT restriction).

Charge Balance is the balance in the BESS of the charge of it, its energy inputs and outputs.

Table 11 shows, between others, the net income a BESS will have currently in Spain. However, in this report was said that hypothetically when Spain has its own grid code there will be an availability fee as it is nowadays in UK.

As explained in Section 6.2, the availability fee has been checked from the Tender Report (May 2018) from National Grid. The tender accepted to provide primary frequency control with a BESS type of 2.4MW has the next characteristics: 47.88€/h of power availability and a total of 5840 hours of utilization in one year. Next equation (9.1.2.1) calculates the availability fee for the whole lifetime of the wind park.

$$\frac{47.88 * 5840 * 15}{2.4} = 1.74x10^{6}€ \quad (9.1.2.1)$$

Bearing in mind that the optimization solved for a higher MW ESS and that there were no tenders with that storage capacity, this income is taken. Then results should be in the order of the equation result (9.1.2.1).

Final net income taking into account the availability fee for Scenario 1 = 1.7 x10^{8} €

Final net income taking into account the availability fee for Scenario 2 = 3.46 x10^{8} €

9.1.3 Wind park optimization with FESS

$\alpha_{low} = 30\ \%$

$\alpha_{high} = 100\ \%$

$\gamma = 3\ \%$

$\eta_{+} = 98\ \%$

$\eta_{-} = 98\ \%$

$\lambda_{EpsP} = 150$ €/kW

$\lambda_{EpsS} = 700$ €/kWh

$\lambda_{Dis} = 0.00007$ €/kWh

The losses due to degradation in a FESS are almost insignificant. From an American manufacturer, it was checked that a flywheel could have 1 million of discharges with no degradation (as explained in Section 3), and having into account that from one FESS it is possible to be obtained 25MWh then, with a quotation price of 700 €/MWh from manufacturer,

$$\frac{25 * 700}{25 * 1} = 0.00007\frac{€}{\mathrm{MWh}} \quad (9.1.3.1)$$

Eq. 9.1.3.1 shows the extremely low cost of degradation due to the lifetime of a FESS.

Table 12 and 13 shows the mathematical optimization results for a wind park and a FESS.

Table 12 FESS size results third study case (own elaboration)

Days for the Scenarios 1 and 2	FESS Power (MW)	FESS Energy Capacity (MWh)
31st of January	4.76	3.11
3rd of March	9.07	10.68

Table 13 Results for the two scenarios of the third study case (own elaboration)

Days for the Scenarios 1, 2	Net income (€)	Total Energy sold to the grid (MWh)	Charge Balance (MWh)
31st of January	1.678 $x10^8$	3.702 $x10^5$	12.335 $x10^6$
3rd of March	3.438 $x10^8$	1.338 $x10^6$	47.628 $x10^6$

As happened in the precious study case with the BESS, the high growth in the net income is basically due to the total energy sold to the grid and the size of the FESS.

Because of there was no any Tender with a Flywheel in the past National Grid UK Tender market then the same amount has been added.

Final net income taking into account the availability fee for Scenario 1 = 1.69 $x10^8$ €

Final net income taking into account the availability fee for Scenario 2 = 3.46 $x10^8$ €

9.1.4 Wind park optimization with FESS + BESS

This scenario was created in order to accomplish the goal of this project: Primary frequency control + power smoothing.

Studying the data collected from free open-source databases, it was checked that there are not high variations between seconds regarding wind speed data. Then, it was thought that the flywheel could achieve the goal of primary frequency control and the battery the one of power smoothing having a constant value for every day of the year.

The firm constant value of the battery has been calculated from the average power generation of the worst day of the park. It allows the WP to imitate the functioning of a fully controllable fuel based power plant, helping this way the integration of the WP into the grid.

Having this regarded output from the battery we will have all possible fluctuations over the year covered from the BESS. Due to that, the BESS is going to have a high dimension. Another point why it was not used a flywheel for that is because since it is much expensive, having a big FESS will not be as economically feasible as having a big BESS.

Both Scenarios designed before (Scenario 1 for 31st of January and Scenario 2 for 3rd of March) have been studied.

The parameters are the same than the ones used for study cases 2 and 3. All equations about primary frequency control used for this study case are the same than for the study cases 2 and 3. However, the objective equation has been a bit modified from equation (8.3.5). Now there are added the capital and degradation costs of both ESS. Check equation (9.1.4.1),

$$Z = -\mathrm{C}_{S_{FESS}} - \mathrm{C}_{S_{BESS}} + C_{\mathrm{deg}_{FESS}} + C_{\mathrm{deg}_{BESS}} + I_{m,t} + I_{fr,t} \quad (9.1.4.1)$$

The equations added to provide power smoothing are defined as:

Parameter $EmaxB$ has been defined as the difference between the power generated by the WP by the 20 turbines in one month minus the average of the power generated in that month to carry out the power smoothing. The average of the power generated of a month is very representative.

The state of charge is represented in equation (9.1.4.2)

$$\mathrm{EpsS}_C(t) - \mathrm{EpsS}_C(t-1) = \varepsilon_{loss_{comEpsP_{BESS}}} - \mathrm{EpsS}_{loss} + \mathrm{EmaxB} \quad (9.1.4.2)$$

For the size of the BESS for power smoothing equations (9.1.4.3) and (9.1.4.4) are defined,

$$\mathrm{EpsPB} \geq \varepsilon_{loss_{comEpsP}} + \mathrm{EmaxB}\frac{Thh}{Ts} \quad (9.1.4.3)$$

$$\mathrm{EpsP} \geq \mathrm{EpsS}_{loss\_BESS} + \mathrm{EmaxB}\frac{Thh}{Ts} \quad (9.1.4.4)$$

Results of providing both services are shown in Tables 14 and 15 for scenarios 1 and 2.

Table 14 FESS and BESS size results fourth study case (own elaboration)

Days for the Scenarios 1, 2	FESS Power (MW)	FESS Energy Capacity (MWh)	BESS Power (MW)	BESS Energy Capacity (MWh)
31st of January	1.50	3.00	35.26	160.28
3rd of March	5.60	9.06	36.68	540.41

Table 15 Results for the two scenarios of the fourth study case (own elaboration)

Days for the Scenarios 1, 2	Net income (€)	Total Energy sold to the grid (MWh)	Charge Balance FESS (MWh)	Charge Balance BESS (MWh)
31st of January	1.15×10^8	3.270×10^5	10.709×10^6	46.941×10^7
3rd of March	2.15×10^8	1.292×10^6	30.873×10^6	181.601×10^7

Final income taking into account the availability fee for Scenario 1= 1.16 x10^8 €

Final income taking into account the availability fee for Scenario 2= 2.16 x10^8 €

In this Table 15 is easily checkable how the charge balance in the BESS is more demanding in terms of MWh in comparison with the one of the FESS.

The FESS is doing the primary frequency control, it implies that the charging balance will be more constant than for the BESS since the FESS follows frequency variations and this are not too big. BESS needs to smooth the curve and it implies a bigger power curve eliminating this way peaks and extreme slopes. These variations are high due to wind conditions.

Figure 40 shows short and mid-term services provided by FESS and BESS respectively.

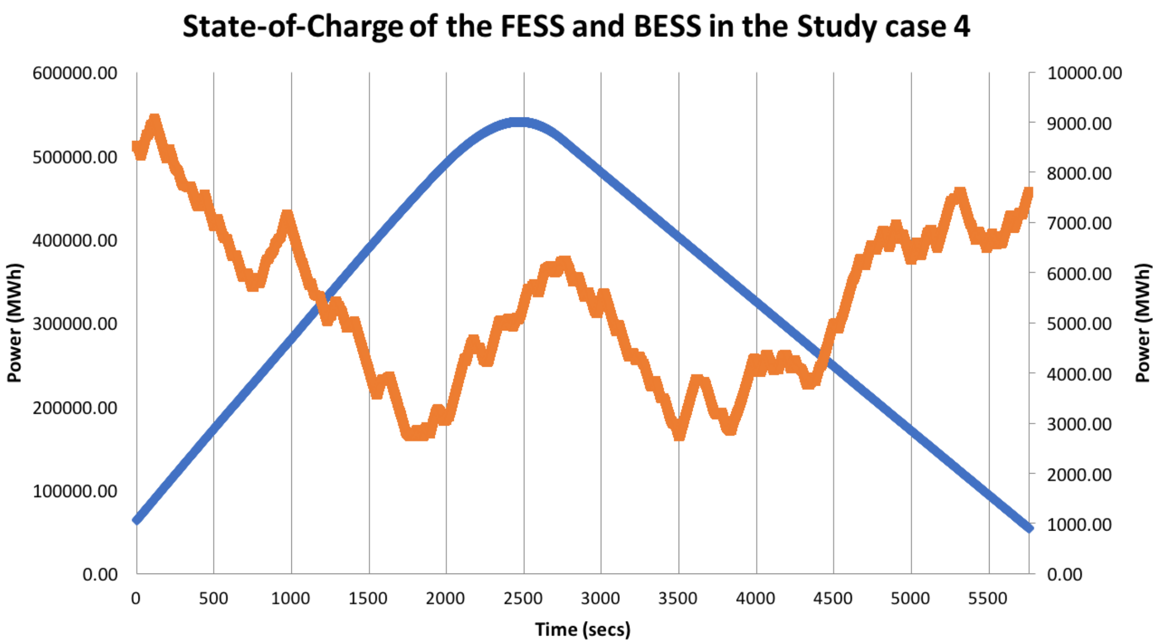


Figure 40 FESS and BESS State-of-Charge for short and mid-term services in Study Case 4 (own elaboration)

The final scheme to achieve the goal of this project is the one shown in Figure 41. It is remarkable from the scheme that the battery and the flywheel use different power converters due to they have different magnitude and the inverter can't be used for both.

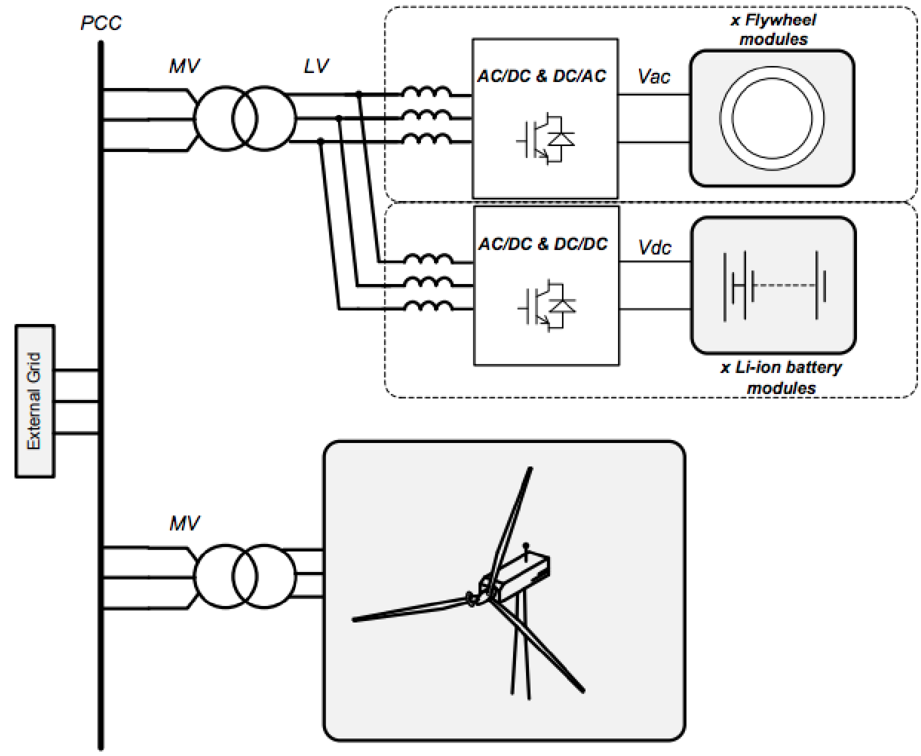


Figure 41 Final configuration scheme WP + FESS + BESS (own elaboration)

10 Economical and technical results discussion

Firstly, it is remarkable to say that precision in the results are extremely based on the precision of the data collected from the free open-source databases utilized in this project.

Study cases

With no ESS it is possible to have a primary frequency control thanks to the control drop done by the power electronics of the aero generator but at high price, operating always at deloaded mode, WTs operate with a 10 % margin (90 % capacity).

Having an energy storage system, solves this problem. The WT operator will be able to extract the maximum available power from the wind.

Economically, not having an ESS solution, will represent a better investment because there is no need to pay for the ESS. However, it does not represent a higher income. With “bad days” such as the 3rd of March, the WT cannot provide enough power reserve and the ESS system acts more appropriately giving support to the grid and so, generation income.

Even so, comparing it with a BESS, the net income does not have a super plus, it is a 4 % higher than with no ESS. In addition, a BESS system gives the wind park operator the security to participate in the tender market for the availability fee income. When the availability fee is introduced then final income is a 5% higher and that means 12 x10^6 € (considerable amount).

When comparing a BESS and a FESS solution for the same service (Study cases 2 and 3, provision of primary frequency control), it is easily checkable that mainly all the results are similar but the balance of charge. Since the FESS has much less losses (both accounting on self-discharge and cycling ones), the charge balance is considerably lower with a FESS solution than with a BESS.

For the hybrid solution, it is understandable that the net income is much lower since two storage systems need to be bought. Nonetheless, as said before, to provide to the grid primary frequency control and power smoothing it is needed an ESS. The grid needs to be supported. It is important to notice though, that the size of the battery (and thus the associated costs) is quite remarkable since it is operated to make the output of the wind park flat at all times. This is an extreme situation, proposed as a proof-of-concept of the application of the battery to make the output of the wind park fully controllable, as the output of a fuel-based synchronized generating system.

11 Environmental and social impact

11.1 Environmental impact

The environmental impact is an important point of study considering the quantity of materials that compose one single lithium-ion battery, a flywheel, a wind turbine and the land used for the wind park. The next Figure 42 is general for any life cycle assessment of a product:

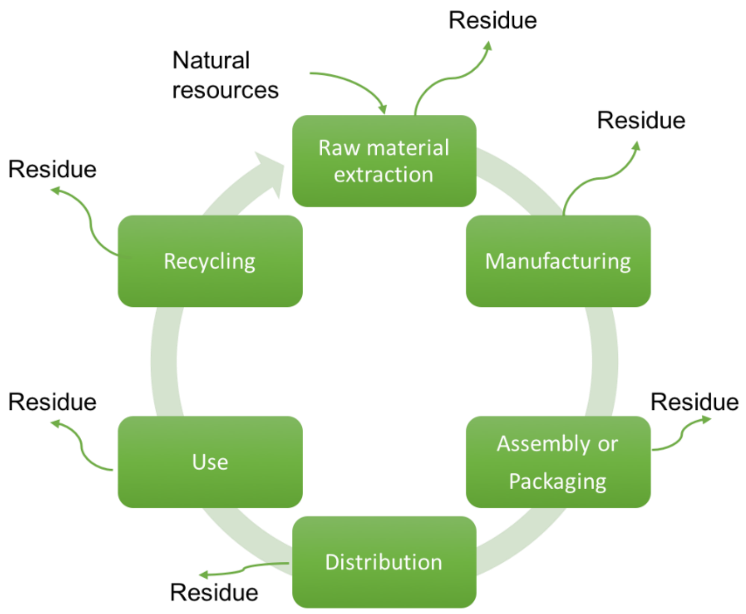


Figure 42 Life cycle assessment (own elaboration)

In every step in the life cycle of a product it is possible to find residues. In this project, there are lithium-ion batteries, flywheels and a wind turbine technologies and their respective environmental impact study, focused on the last part of the life cycle, the ***Recycling***:

Wind Parks

Wind parks are not free of environmental impacts. These environmental impacts are a serious concern for the wind energy industry and include wildlife safety, bio-system disturbance, noise or visual pollution [60], [61] .

- Wildlife Safety: it goes from injuries due to collision with the turbine towers to death by colliding with the blades. When a wind park is located on ridges, upwind slopes or close to the bird migration routes the mortality rate increases. The extra work the birds have to do to avoid the wind park from their migratory route reduces their survival rate.
- Bio-system disturbance: While constructing the wind park, road construction, may affect the local bio-system as well as the water or oil utilization during this work. Other problem is the soil erosion if surface plants are removed. A wind park of 20 turbines can occupy a space of 1 km square. However, the turbines and equipment only use a 1 % of this space. Any case, the land must be cleaned and roads need to be built to transport the machinery.
- Noise impact: There are two types of noise produced by a wind turbine, mechanical type and aerodynamic type. Mechanical noise type can be reduced from the beginning, the design step. The aerodynamic noise type is produced by the flow of the air over the blades. Since modern turbines can rotate to face the wind upward direction, noises can come from different directions at different times. To have a control on the noise level, each region stablish a minimum separation distance between wind parks and habitations. In Spain, the distance is set between 500 and 1000 meters.
- Visual Impact: It varies according to the color, size, distance from the households, shadow flickering, the movement of the blades or them stopped, local topographies, and local landscapes between viewers and turbines.

Counting the environmental impact in energy produced (kWh), wind energy has 21 times less environmental impact than if producing the same energy with oil, 10 times less than nuclear energy and 5 times less than gas. Wind energy is unlimited and slows down the releasing of greenhouse gasses. However, the 60 % of the wind parks in Spain will have more than 15 years by 2020. It means that the components of the aero generators should be recycled in a near future it is an urgent fact due to the big quantities of aero generators that are installed [48].

The blades are the most sensitive materials in order to recycle them and because of that new alternatives are needed. Between 2017 and 2025, 4500 blades will be needed to be changed and without any regulations about the recycling of them, they will go directly to the land field. Nevertheless, there are two companies, EDPR (Energias de Portugal S.A., Renováveis, Renewable department) and Thermal Recycling of Composites (TRC), a spin-off of Spain's National Research Council (CSIC) that agreed last year, 2017, to boost the recycling of the decommissioned wind turbine blades. The system is called R3FIBER and will provide a second useful life to the valuable component carbon fiber among others. The technology, aims to the completely reuse of the blade materials without producing any waste (no resins). It is produced a thermochemical transformation which process produces reusable fibers (fiberglass and carbon fiber). The resulting fibers are similar to the composites used to manufacture the original blades, a key factor that enables their subsequent reuse [48], [62].

The other parts of the aero generator are used also in other industries and there are already regulations about how to recycle them.

Lithium-ion Batteries

As mentioned in Yuan et al. [63], the embedded energy in battery materials represents a high consumption of primary energy. Primary energy is the energy that has not being refined into secondary energy. It is the energy used from different activities and materials used to manufacture a battery. For example, with a graphite battery pack production there are three different primary energy used: one is the energy embedded in the battery materials, the second one is the energy used for cell production and the third one is the energy used for assembly the battery. After reading this paper it is possible to obtain the conclusion that a lithium-ion battery can deliver 1029 times the energy it needs to be produced (ideally with no fatigue after the 1029 discharges and charges of the battery).

Next Figure 43 shows a general battery manufacturing process from the same paper Yuan et al. [63].

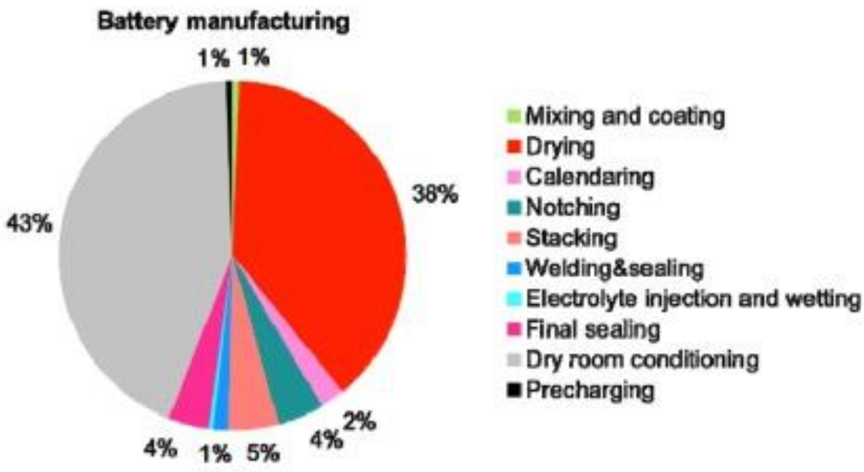


Figure 43 General lithium-ion battery manufacturing [63]

From Hao et al. [64], having the main lithium-ion battery types it is concluded that the three types of lithium-ion batteries, LFP, NMC and LMO, have GHG emissions during production, it is calculated: 3061 kgCO_2-eq, 2912 kgCO_2-eq and 2705 kgCO_2-eq, respectively (the study based its results with a 28kWh battery).

Next Figure 44 from IRENA shows the battery market supply chain [10].

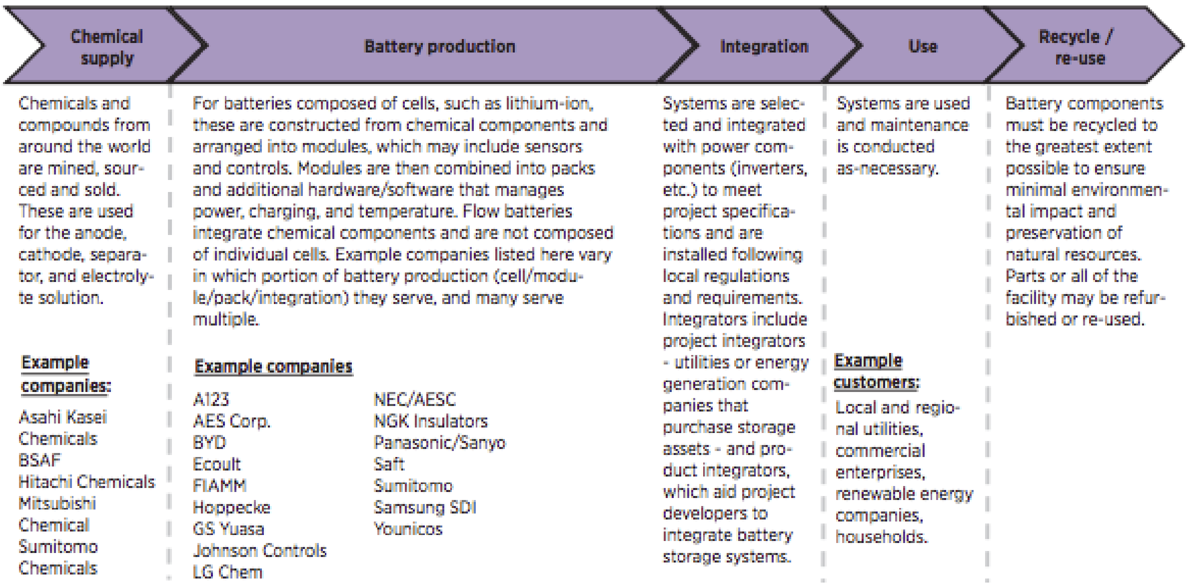


Figure 44 Battery Market supply [10]

First and last steps of the battery market supply are the most important in terms of environmental impact. In this section, it is studied the last one, the Recycle/re-use. There are different aspects to consider when facing a lithium-ion energy requirement, recycling and disposal. Four main steps are considered: Collection, Disassembly, Material Recovery and Reuse.

- Collection: hazardous metals transport regulations (cobalt, zinc, manganese, copper, nickel and lithium)
- Disassembly: Non-uniform shapes and materials, plastic cases crushed, some manual disassembly required
- Material Recovery: Lithium currently not recycled, high value metals (such as cobalt, copper and aluminium, plastic captured as plastic fluff
- Reuse: High value metals reused in other applications (like nickel, cobalt and silver, can be recovered if batteries are properly recycled), mixed plastic more difficult to reuse

In the next Table 16 are shown the main components of the lithium-ion Battery types LFP, NMC and LMO.

Table 16 Main lithium-ion battery components [63]

Battery Components	LFP	NMC	LMO
Anode Active Materials	24.4%	28.2%	33.6%
Graphite	15.2%	18.3%	14.7%
Binder	2.1%	2.4%	2.5%
Copper	12.4%	11.4%	10.9%
Wrought aluminum	20.3%	19.7%	18.7%
Electrolyte: LiPF6	2.7%	1.9%	1.9%
Electrolyte: EC	7.8%	5.4%	5.4%
Electrolyte: DMC	7.8%	5.4%	5.4%
Plastic: PP	1.9%	1.7%	1.7%
Plastic: PT	0.3%	0.3%	0.3%
Plastic: PET	1.3%	1.2%	1.2%
Steel	1.5%	1.4%	1.4%
Fiberglass	0.3%	0.4%	0.3%
Coolant: Glycol	1.0%	1.0%	0.9%
Battery Management System(BMS)	1.0%	1.3%	1.1%

From the European Union Legislation, Directive 2006/66/EC [65], are trying to reinforce recycling in batteries and accumulator but still the regulations are not enough since manufacturers and users are not doing so.

The main difficulty in terms of recycling a lithium-ion battery is the wide variety of the models and consequently the elements/materials used for the manufacturing.

Currently, there are processes available for lithium-ion batteries that recover cobalt, nickel and copper from battery waste. However, as a common ending, the cell content is combusted releasing metal pollutants to the atmosphere. The ash is used for a second life in the construction industry but this is clearly not sustainable at all. The actual situation is that the 95% of lithium-ion batteries are riskily stockpiled or just land filled somewhere (mostly are transported to undeveloped countries' land filled). When this happens, the metals can leach into the soil and water. Only 5% are sent to recycling facilities [66], [67].

Flywheels

A FES can be considered as a clean substitution technology for regular electrochemical-based energy storage. The FES is made of non-hazardous basic metals and carbon fibers and it has a limited impact during production, operation (no emissions), and disposal because there is not chemical management. Flywheels are made from almost 100% steel, which is not toxic.

There is not much information about environmental aspects of flywheel because the use of this technology is not fully developed [68].

In the next Table 17, it is shown the typical components of a flywheel:

Table 17 Typical components of a Flywheel [69]

Flywheel Components	(%) Content	Embeded CO_2 (kg CO_2/kg)
Iron	95.5%	1.91
Nickel	1.83%	12.4
Chromium	0.80%	5.4
Manganese	0.70%	3.5
Carbon	0.40%	0
Molybdenum	0.25%	32.2
Silicon	0.20%	13.5

Flywheel vs Battery Carbon Footprint

Schneider Electric has developed a Carbon Footprint Tool that calculates the differences between a Flywheel and a Battery emissions in ton of CO_2-eq.

As a first impression, it seemed that a Flywheel are less dangerous for the environment since the materials used for its manufacturing do not contain any special hazardous element as in batteries. However, Schneider electric demonstrated the contrary.

The battery used for the Schneider study was a VRLA battery, that in general terms is much worse in comparison with a lithium-ion type as we can check in Table 18 from a study Schneider Electric did before the comparison with a flywheel [70].

Table 18 VRLA vs Li-ion battery comparison [70]

Battery attribute	VRLA	Li-ion
Chemistry	Lead-acid	LMO/NMC
Rated power capacity	1 MW	1 MW
Runtime at 25°C (77°F)	6 minutes	6 minutes
Calendar life at 25°C (77°F)	5 years	17 years
Battery service life at 25°C (77°F)	4 years	12 years
Battery footprint	5.4 m^2 (59 ft^2)	2.2 m^2 (23 ft^2)

After having noticed this information, Schneider Electric did the study of the carbon footprint and released that even using a “bad” attribute battery (VRLA) the carbon footprint was much better than for a flywheel.

For using the Schneider Electric Tool, it has been chosen as a location USA to be a reasonable input because in that country there is already a proven company that manufactures Flywheels, Active Power [69] that provides apart from flywheel data carbon emissions (kg/kWh).

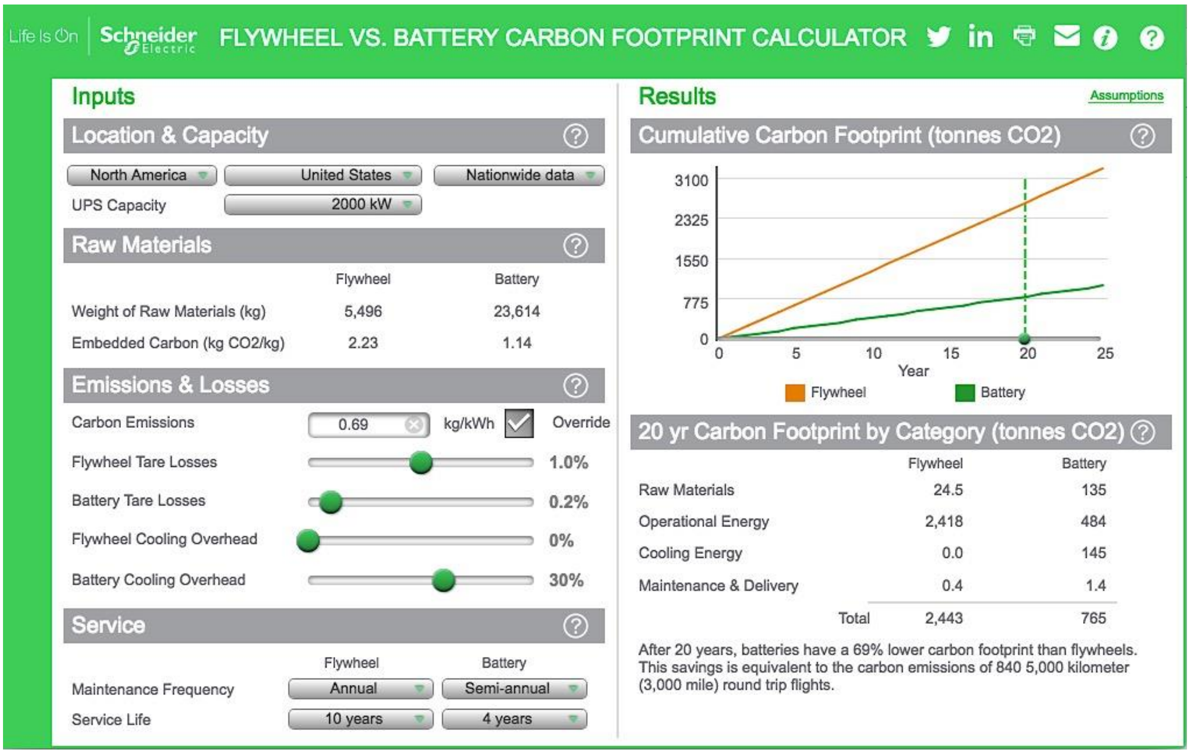


Figure 45 TradeOff Launcher footprint calculator [71]

The conclusions of the Figure 45 above is as it says, that the footprint over 20 years is 69% higher than a bad VRLA battery. Then, just doing a small extrapolation, since a lithium-ion has a battery service of 12 years the footprint over 20 years will be much smaller than for a VRLA battery therefore, the flywheel footprint could rise in a hypothetical case up to 80% higher.

The conclusion of Schneider Electric is that the definition of “green” for a Flywheel does not match anymore. There are some carbon savings in raw materials cooling and maintenance it does not compensate the operational energy over a lifetime that it needs [72].

For this project, the electricity will always be taken from a wind park. Then, the footprint of the flywheel will be significantly reduced due to the utilization of a renewable source for its operability.

11.2 Social impact

This project is thought to have an indirect social impact improving air quality conditions and lifestyle. Renewable energies and the transition to them will make an improvement of current society. Moreover, taking into consideration that every year is estimated that 7 million people have a premature death due to air quality, the transition to renewable energies should be a priority step all over the world [73].

Another important point is that energy policies are changing. There are already more than 100 cities in the world that get at least 70 % of their electricity from renewable sources (hydro, geothermal, solar and wind mostly) and they need storage systems to complete their approach to get 100 % renewables [74]. Indeed, more than 40 cities are currently generating at 100% renewable capacity (the US city of Burlington, Basel in Switzerland, and the Icelandic capital Reykjavík between others) [75]. In addition, more than 600 cities are generating electricity in a lower percentage but reporting a good generation. It means that people that live in those countries are having a transition time in the energy field as well as they are developing a better society thinking in the future generations, more conscious with the environmental impact that the electricity production produces daily [74].

12 Plan

This projects has had a duration of 4 months gross. First meeting with the tutor to complete the first Table of content was done middle February. From that time on, the project has had different periods of time depending on the different activities needed to complete it.

The project could be divided as it is already done in the Methodology section. However here it is included the time to do every step through the next Figure 46 that represents a Gantt diagram.

A total of 8 weeks to complete the research, then 5 weeks to check the regulations of grid codes and day ahead market and while doing that, checking for data collection for those regulations and for the wind park during 4 weeks. Later, there were settled the different study cases to use for the optimization in GAMS using almost other 4 weeks.

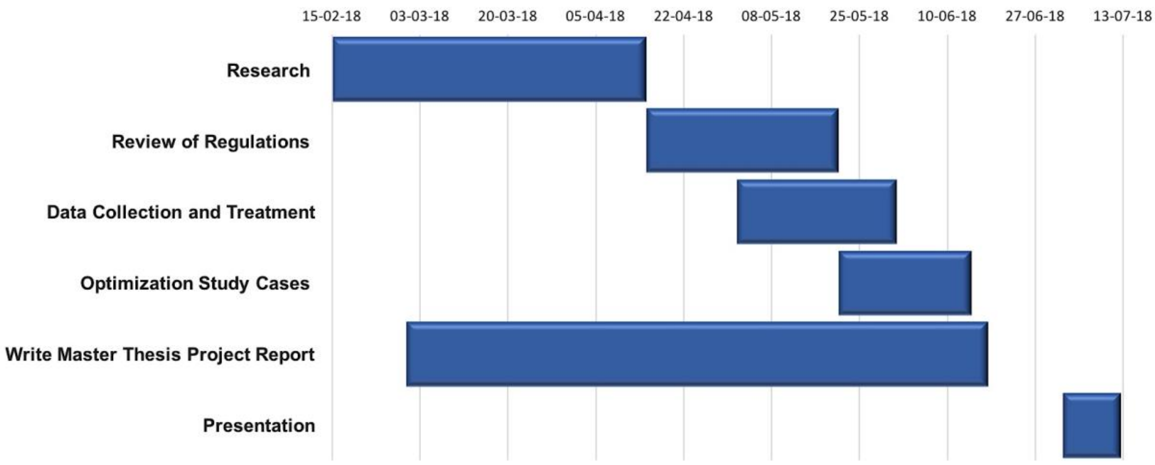


Figure 46 Gantt diagram (own elaboration)

13 Project realization cost

The principal costs that need to be taken into account for the student realization of this project are the next:

- The Final Master Thesis is equal to 30 ECTS. One ECTS credit is equal to 25 hours of class-work. For this master thesis 750 hours have been dedicated including study, editions of the memory and work with the tutor. Equation (10.1), shows the approximate cost in euros of an average student salary from UPC (8 €/h).

$$\text{Approx student cost} \approx Hours\ dedicated\ thesis * Student\ Salary \qquad (10.1)$$

- The materials utilized for this Final Master Thesis is a laptop of 1200 € with already 7 years of utilization plus two software licenses, MathWorks with an annual cost of 800 € and GAMS with a complete cost of 1600 € cost of academic price.

$$\text{Material cost} \approx \left(\frac{Hours\ dedicated\ thesis}{7years}\frac{1year}{8760hors}\right) * Cost\ Laptop + \sum\left(\frac{Hours\ dedicated\ thesis}{1years}\frac{1year}{8760hors}\right) * cost\ license \qquad (10.2)$$

- Basic student material, approximately 20 €

The Final Master Thesis has been developed inside the installations of UPC at CITCEA department. No cost of other materials (cables, adaptors, lights) are calculated.

- Total of the project realization cost = 6171 €

14 Conclusions

The goal of this project has been completed and the study of the primary frequency control and power smoothing with a hybrid energy storage system has been proven along with the proposed study cases.

The first study case addresses the base case, in which no ESS is installed in the wind park (total net income of 3.29×10^8 €). Then, the second and third study cases proposes the installation of an ESS solely based on either flywheels or batteries for providing the service of primary frequency control. As compared to the first study case (base case), it is worth noting that the net income for the wind park during the 15 years of time horizon for the project is sensibly incremented (3.46×10^8 € for study cases 2 and 3 in the worst-case scenario). This is because both batteries and flywheels success in providing the required power reserves for participating in the market of the ancillary service of primary frequency control, while turbines can effectively be operated near their point of maximum aerodynamic efficiency, thus maximizing the profit in the day ahead market.

Then, in study case 4, batteries provide the service of power smoothing of the wind park while flywheels performs the service of primary frequency control. So in this study case, a hybrid ESS is adopted. The aim for the batteries is to provide a firm (constant) power output to the grid by the wind park. Although such firm (constant) output of the wind park at all times would seem rather extreme, this is evaluated as a proof-of-concept for the battery to permit the wind park to mimic the behaviour of fully controllable fuel based power plant. Such service of the battery would facilitate the integration of wind parks into grids and markets making them totally manageable. In turn, flywheel provides the service of primary frequency control. The aim is to control the power output of the WP through a droop control to mitigate the problems caused in the grid due to frequency fluctuations.

For this study case 4, final results show that for worst-case scenario (high fluctuation of wind speed), the ESS size is 5.6 MW FESS and a 36.68 MW BESS. This yields a total net income of 2.16×10^8 € for the life time of the WP.

The hybrid ESS mathematical optimization model developed in GAMS is general, flexible and scalable to any ESS. It can be also utilised for testing any output power profile of the wind park (e.g. firm, stepped, according to maximum energy price, and etcetera). It is able to provide an accurate solution. In addition, this model could be used as a tool for existing wind parks that are planning to install an ESS.

Acknowledgements

I would like to thank my thesis advisor Dr. Francisco Díaz González for having taught and supported me during the whole process of this master thesis, and also for giving me a space at CITCEA department were I used helpful equipment to develop it.

Secondly, I would like to thank my family (dad, mum and sister) for supporting me from the distance and last but not least I would like to thank Alejandro for being there for me during stressful periods.

References

[1] S. Holly y S. Callery, «Global Climate Change Vital signs of the Planet,» Earth Science Communications Team at NASA's Jet Propulsion Laboratory, 2018. [En línea]. Available: https://climate.nasa.gov/. [Último acceso: 15 03 2018].

[2] European Parliament, «News European Parliament,» 17 01 2018. [En línea]. Available: http://www.europarl.europa.eu/news/en/press-room/20180112IPR91629/meps-set-ambitious-targets-for-cleaner-more-efficient-energy-use. [Último acceso: 21 03 2018].

[3] WindEurope asbl/vzw, «Wind Europe,» 2018. [En línea]. Available: https://windeurope.org/about-wind/statistics/european/wind-in-power-2017/#findings. [Último acceso: 9 April 2018].

[4] Asociación Empresarial Eólica, «aeeolica,» 2017. [En línea]. Available: https://www.aeeolica.org/en/. [Último acceso: 10 April 2018].

[5] IEA WIND , «IEA WIND 2013 Annual Report,» 2014. [En línea]. Available: https://community.ieawind.org/HigherLogic/System/DownloadDocumentFile.ashx?DocumentFileKey=3555ace8-bf68-41eb-97b1-5f7973ed37ca. [Último acceso: 12 April 2018].

[6] C. Vazquez-Hernandez, J. Serrano-Gonzalez y G. Centeno, «A Market-Based Analysis on the Main Characteristics of Gearboxes Used in Onshore Wind Turbines,» Energies, 2017.

[7] E. Á. Pelegry, M. A. Peñalba, Á. A. Vargas, Á. M. Belmonte, E. B. Massagué, J. C. F. D. González, J. L. F. Díaz, F. G. A. G. Expósito, P. L. Gallego, L. M. A. M. Marcolini, J. L. M. Ramos, E. M. J. M. M. Ferramola, P. O. Rosell, J. I. P. Arriaga, J. P. d. Cabrero, J. M. R. Mediavilla, C. R. J. R. Santos, E. R. Ramos, J. S. Cifuentes, A. S. Andreu y A. S. , El Almacenamiento De Energía En La Distribución Eléctrica Del Futuro, J. P. d. V. C. Ángel Arcos Vargas, Ed., Madrid: Grafilia, S.L., 2017, p. 180.

[8] Independent Electricity System Operator, «High Performance Flywheel Energy Storage Systems: Temporal Power,» 2017. [En línea]. Available: http://www.ieso.ca/en/powering-tomorrow/technology/high-performance-flywheel-energy-storage-systems-temporal-power. [Último acceso: 19 April 2018].

[9] F. Diaz-Gonzalez, A. Sumper, O. Gomis-Bellmunt y R. Villafafila-Robles, «A review of energy storage technologies for wind power applications,» Science Direct, 2012. [En línea]. Available: https://www.sciencedirect.com/science/article/pii/S1364032112000305. [Último acceso: 24 April 2018].

[10] International Renewable Energy Agency, IRENA, «BATTERY STORAGE FOR RENEWABLES: MARKET STATUS AND TECHNOLOGY OUTLOOK,» January 2015. [En línea]. Available: https://www.irena.org/documentdownloads/publications/irena_battery_storage_report_2015.pdf. [Último acceso: March 2018].

[11] S. Jiang, H. Wang y S. Wen, «Flywheel energy storage system with a permanent magnet bearing and a pair of hybrid ceramic ball bearings,» *Journal of Mechanical Science and Technology 28 (12) (2014) 5043~5053,* 2014.

[12] J. G. Bai, X. Z. Zhang y L. M. Wang, «A Flywheel Energy Storage System with Active Magnetic Bearings,» *SciVerse ScienceDirect,* 2012.

[13] International Renewable Energy Agency, IRENA, «Electricity Storage and renewables: Costs and markets to 2030, ISBN 978-92-9260-038-9,» 2017. [En línea]. Available: http://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Oct/IRENA_Electricity_Storage_Costs_2017.pdf.

[14] Temporal Power, «Flywheels for Renewable Integration,» [En línea]. Available: http://temporalpower.com/wp-content/uploads/2014/06/Applications-Renewable-Integration.pdf. [Último acceso: 19 April 2018].

[15] F. Monforti y I. Gonzalez-Aparicio, «Comparing the impact of uncertainties on technical and meteorological parameters in wind power time series modelling in the European Union,» Science Direct, 2017. [En línea]. Available:

https://www.sciencedirect.com/science/article/pii/S0306261917312515. [Último acceso: 19 April 2018].

[16] G. Ren, J. Jinfu, W. Jie, G. Yufeng y Y. Daren, «Overview of wind power intermittency: Impacts, measurements, and mitigation solutions,» Science Direct, 2017. [En línea]. Available: https://www-sciencedirect-com.recursos.biblioteca.upc.edu/science/article/pii/S0306261917308346. [Último acceso: 19 April 2018].

[17] Energy Storage Association, [En línea]. Available: http://energystorage.org/. [Último acceso: 19 April 2018].

[18] F. Diaz-Gonzalez, M. Hau, A. Sumper y O. Gomis-Bellmunt, «Coordinated operation of wind turbines and flywheel storage for primary frequency control support,» Science Direct, 2015. [En línea]. Available: https://www-sciencedirect-com.recursos.biblioteca.upc.edu/science/article/pii/S0142061514007893. [Último acceso: 24 April 2018].

[19] L. Johnson, F. Diaz-Gonzalez, O. Gomis-Bellmunt, C. Corchero-Garcia y M. Cruz-Zambrano, «Methodology for the economic optimisation of energy storage systems for frequency support in wind power plants,» Science Direct, 2014. [En línea]. Available: https://www.sciencedirect.com/science/article/pii/S0306261914009787. [Último acceso: 24 April 2018].

[20] A. Motin Howlader, N. Urasaki, A. Yona, T. Senjyu y A. Yousuf Saber, «A review of output power smoothing methods for wind energy conversion systems,» Science Direct, 2013. [En línea]. Available: https://www-sciencedirect-com.recursos.biblioteca.upc.edu/science/article/pii/S1364032113003316. [Último acceso: 24 April 2018].

[21] J. Wang y W. X, «A Control Strategy for Smoothing Active Power Fluctuation of Wind Farm with Flywheel Energy Storage System Based on Improved Wind Power Prediction Algorithm,» Scientific Research, 2013. [En línea]. Available: https://pdfs.semanticscholar.org/19fa/d9e8ebb2833ef5c7937104962edb559eef2c.pdf. [Último acceso: May 2018].

[22] M. Khalid y A. V. Savkin, «Minimization and control of battery energy storage for wind power smoothing: Aggregated, distributed and semi-distributed storage,» Science Direct, April 2014. [En línea]. Available: https://www-sciencedirect-com.recursos.biblioteca.upc.edu/science/article/pii/S0960148113005223. [Último acceso: March 2018].

[23] Global Wind Energy Council, «Wind Energy Outlook, 2016,» 2016. [En línea]. Available: http://gwec.net/publications/global-wind-energy-outlook/global-wind-energy-outlook-2016/. [Último acceso: 19 April 2018].

[24] ACCIONA, «ACCIONA - Press Room,» 2017. [En línea]. Available: https://www.acciona.com/news/acciona-starts-up-first-hybrid-wind-power-storage-plant-spain-using-batteries/. [Último acceso: 12 April 2018].

[25] A. Todd, «NEON EN,» 2017. [En línea]. Available: https://www.neoen.com/wp-content/uploads/2017/07/FINAL-press-release-Tesla_Neoen-07072017.pdf. [Último acceso: 12 April 2017].

[26] S. Verbruggen, «Wind Power Monthly,» 2016. [En línea]. Available: https://www.windpowermonthly.com/article/1416407/hybrid-storage-system-looks-irelands-services-market. [Último acceso: 12 April 2018].

[27] J. Parnell, «Energy Storage News,» 2016. [En línea]. Available: https://www.energy-storage.news/news/flywheel-battery-hybrid-system-installed-in-ireland. [Último acceso: 12 April 2018].

[28] International Renewable Energy Agency, IRENA, «IRENA (2016), 'Scaling up Variable Renewable Power: The Role of Grid Codes',» IRENA Publications, 2016.

[29] European Network of Transmission System Operators, ENTSO-E, [En línea]. Available: https://www.entsoe.eu/.

[30] EUR - Lex Access to European Union law, 2016. [En línea]. Available: https://eur-lex.europa.eu/legal-content/IT/ALL/?uri=CELEX:32016R0631. [Último acceso: 19 April 2018].

[31] Agencia Estatal Boletín Oficial del Estado [ES], «REGLAMENTO (UE) 2016/631 DE LA COMISIÓN de 14 de abril de 2016 que establece un código de red sobre requisitos de conexión de generadores a la red,» 2016. [En línea]. Available: https://www.boe.es/doue/2016/112/L00001-00068.pdf. [Último acceso: 19 April 2018].

[32] IEC, International Electrotechnical Commision, «Technical Specification 62786:2017,» IEC publications, 2017.

[33] F. Díaz-González, M. Hau, A. Sumper y O. Gomis-Bellmunt, «Participation of wind power plants in system frequency control: Review of grid code requirements and control methods,» Science Direct, 2014.

[34] Agencia Estatal Boletín Oficial del Estado [ES], «BOE-A-2009-8813, BOE-A-1998-20053,» Ministerio de Industria, turismo y comercio , 2009. [En línea]. Available: https://www.boe.es/buscar/doc.php?id=BOE-A-1998-20053. [Último acceso: 3 May 2018].

[35] Agencia Estatal Boletin Oficial del Estado, «RESOLUCIÓN de 30 de julio de 1998, de la Secretaría de Estado de Energía y Recursos Minerales, por la que se aprueba un conjunto de procedimientos de carácter técnico e instrumental necesarios para realizar la adecuada gestión técnica del sistema eléctrico.,» [En línea]. Available: https://www.boe.es/buscar/doc.php?id=BOE-A-1998-20053. [Último acceso: 3 May 2018].

[36] Agencia Estatal Boletín Oficial del Estado [ES], 2006. [En línea]. [Último acceso: 3 May 2018].

[37] Asociación Empresarial Eólica, AEE, «Ponencias - AEE,» [En línea]. Available: https://www.aeeolica.org/ponencias/mercados-ajuste/1-Red-Electrica-Espana.pdf. [Último acceso: 3 May 2018].

[38] National Grid UK, 2018. [En línea]. Available: https://www.nationalgrid.com/uk/electricity/balancing-services/frequency-response-services/firm-frequency-response?market-information. [Último acceso: 2 may 2018].

[39] «Interconnected network of Continental Europe 2017,» ENTSO-E, 2017. [En línea]. Available: https://docstore.entsoe.eu/Documents/Publications/maps/2017/Map_Continental-Europe-2.500.000_400dpi.pdf.

[40] P.-T. de Boer, «Accuracy and stability of the 50 Hz mains frequency,» [En línea]. Available: http://wwwhome.cs.utwente.nl/~ptdeboer/misc/mains.html.

[41] REE (Red Eléctrica de España), systema de Inofrmación del operador del systema, [En línea]. Available: https://www.esios.ree.es/es. [Último acceso: 21 may 2018].

[42] ENTSO-E WGAS, «Survey on ancillary services procurement, balancing market design 2016,» 2017. [En línea]. Available: https://docstore.entsoe.eu/Documents/Publications/Market%20Committee%20publications/WGAS_Survey_final_10.03.2017.pdf. [Último acceso: 2018].

[43] Red Electrica España, REE, «La operación del sistema eléctrico y la gestión de los servicios de ajuste,» 2016. [En línea]. Available: https://www.aeeolica.org/ponencias/mercados-ajuste/1-Red-Electrica-Espana.pdf. [Último acceso: 2018].

[44] National Grid UK, «Firm Frequency response,» 2017. [En línea]. Available: https://www.nationalgrid.com/sites/default/files/documents/FFR%20FAQs%20v1.3.pdf. [Último acceso: 5 May 2018].

[45] National Grid UK, «Frequency Response Energy Payment,» 2012. [En línea]. Available: https://www.nationalgrid.com/sites/default/files/documents/17373-Frequency%20Response%20Energy%20Payment.pdf. [Último acceso: May 2018].

[46] National Grid UK, «FFR market information and tender reports,» 2018. [En línea]. Available: https://www.nationalgrid.com/uk/electricity/balancing-services/frequency-response-services/firm-frequency-response?market-information.

[47] National Grid UK, «Firm frequency response interactive guidance,» December 2017. [En línea]. Available:

https://www.nationalgrid.com/sites/default/files/documents/Firm%20Frequency%20Response%20%28FFR%29%20Interactive%20Guidance%20v1%200_0.pdf. [Último acceso: 5 May 2018].

[48] ASOCIACIÓN EMPRESARIAL EÓLICA, «Eólica 2017, La voz del sector,» 2017.

[49] Asociación Empresarial Eólica, «aee,» [En línea]. Available: https://www.aeeolica.org/. [Último acceso: 10 May 2018].

[50] IDAE Instituto para la Diversificación y Ahorro de la Energía, [En línea]. Available: http://atlaseolico.idae.es/meteosim/. [Último acceso: 14 May 2018].

[51] IEC International Electrotechnical Commission, [En línea]. Available: http://www.iec.ch/perspectives/general_public/what_iec_does.htm. [Último acceso: 14 May 2018].

[52] Soda-Pro, «SODA solar radiation data,» MINES ParisTech / Transvalor, 2014-2018. [En línea]. Available: http://www.soda-pro.com/web-services/meteo-data/merra. [Último acceso: 14 May 2018].

[53] Energies, «Generators, Low Voltage Ride-Through Capability Solutions for Permanent Magnet Synchronous Wind,» 2016. [En línea]. Available: http://www.mdpi.com/1996-1073/9/1/59/htm. [Último acceso: 2018].

[54] Gamesa Electric, [En línea]. Available: http://www.gamesaelectric.com/index.php?option=com_content&task=view&id=201&Itemid=333&lang=en. [Último acceso: 5 May 2018].

[55] Siemens Gamesa, [En línea]. Available: https://www.siemensgamesa.com/es-es. [Último acceso: 5 May 2018].

[56] L. Bauer y S. Matysik, «wind-turbine-models.com,» 2011-2018. [En línea]. Available: https://en.wind-turbine-models.com/turbines/156-gamesa-g128-4.5mw. [Último acceso: 5 May 2018].

[57] The Wind Power, «The Wind Power - Wind Energy Market Intelligence,» 2005-2018. [En línea]. Available:

https://www.thewindpower.net/scripts/fpdf181/turbine.php?id=81. [Último acceso: 5 May 2018].

[58] The wind power, «Cortijo de Guerra I (España),» 2018. [En línea]. Available: https://www.thewindpower.net/windfarm_es_2501_cortijo-de-guerra-i.php. [Último acceso: 2018].

[59] The wind power, «Cortijo de Guerra II (España),» 2018. [En línea]. Available: https://www.thewindpower.net/windfarm_es_4418_cortijo-de-guerra-ii.php. [Último acceso: 2018].

[60] K. Dai, A. Bergot, C. Liang, W.-N. Xiang y Z. Huang, «Environmental issues associated with wind energy - A review,» ScienceDirect, 2014. [En línea]. Available: https://www-sciencedirect-com.recursos.biblioteca.upc.edu/science/article/pii/S0960148114007149. [Último acceso: 11 April 2018].

[61] L'Associació Eòlica de Catalunya, EOLICCAT, «Wind Energy,» [En línea]. Available: http://eoliccat.net/la-tecnologia/preguntas-frecuentes/?lang=es. [Último acceso: 2018].

[62] TRC, S.L., «Thermal Recycling of Composites,» 2017. [En línea]. Available: https://www.trcsl.com/. [Último acceso: 11 April 2018].

[63] Science Direct, «Manufacturing energy analysis of lithium ion battery pack for electric vehicles,» 2017. [En línea]. Available: https://www.sciencedirect.com/science/article/pii/S0007850617301099. [Último acceso: April 2018].

[64] MDPI Open Access, «GHG Emissions from the Production of Lithium-Ion Batteries for Electric Vehicles in China,» 2017. [En línea]. [Último acceso: May 2018].

[65] European Commission, «Environment, Batteries & Accumulators,» [En línea]. Available: http://ec.europa.eu/environment/waste/batteries/legislation.htm. [Último acceso: 22 March 2018].

[66] Intertek, «The Future of Battery Technologies – Part V Environmental Considerations for Lithium Batteries,» [En línea]. Available: http://www.intertek.com/uploadedFiles/Intertek/Divisions/Commercial_and_Electrical/Media/PDF/Battery/Environmental-Considerations-for-Lithium-Batteries-White-Paper.pdf. [Último acceso: 22 03 2018].

[67] Li-Cycle , [En línea]. Available: https://www.li-cycle.com/. [Último acceso: 22 03 2018].

[68] Active Power, [En línea]. Available: http://www.activepower.com/en-US/5060/why-flywheel. [Último acceso: 11 April 2018].

[69] Active Power, «Improving Sustainability with Flywheel UPS,» [En línea]. Available: http://www.activepower.com/en-US/documents/3797/wp120-improving-sustainability-with-flywheel-ups. [Último acceso: 19 April 2018].

[70] Schneider Electric, «Battery Technology for Data Centers: VRLA vs. Li-ion,» APC, 2017. [En línea]. Available: http://www.apc.com/salestools/VAVR-A5AJXY/VAVR-A5AJXY_R0_EN.pdf. [Último acceso: 2018].

[71] Shneider Electric, «TradeOff Tool,» [En línea]. Available: https://www.schneider-electric.com/en/work/solutions/system/s1/data-center-and-network-systems/trade-off-tools/flywheel-vs-battery-ups-carbon-footprint-calculator/. [Último acceso: 2018].

[72] Schneider Electric, «Lifecycle Carbon Footprint Analysis of Batteries vs. Flywheels,» APC, 2017. [En línea]. Available: http://www.apc.com/salestools/VAVR-9KZQVW/VAVR-9KZQVW_R0_EN.pdf. [Último acceso: 2018].

[73] CBSN Live News, «The most polluted cities in the world, ranked,» 2018. [En línea]. Available: https://www.cbsnews.com/pictures/the-most-polluted-cities-in-the-world-ranked/. [Último acceso: 2018].

[74] Flourish, «The world's renewable energy cities,» Flourish, February 2018. [En línea]. Available:

https://public.flourish.studio/story/2741/?utm_source=showcase&utm_campaign=story/2741. [Último acceso: 2018].

[75] Positive News, «More than 100 global cities now get he majority of electicity from renewables,» Positive News, February 2018. [En línea]. Available: https://www.positive.news/2018/environment/31568/more-than-100-global-cities-now-get-the-majority-of-electricity-from-renewables/. [Último acceso: 2018].

[76] Ecreativeworks, «House of Batteries,» [En línea]. Available: http://www.houseofbatteries.com/glossary-i-26-l-en.html. [Último acceso: 13 03 2018].